External Radar Calibration Options
Applicable to the WSR-88D Network

Report on Special Project 20
For the Radar Operations Center
Engineering Branch

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Executive Summary

This engineering report explores WSR-88D radar calibration by external means. It reviews availability and feasibility of "calibration aids", equipment and software that will assist in verifying WSR-88D reflectivity measurement and in reducing its uncertainty. Development of four external engineering calibration aids is recommended. To give context to the recommendations, the report categorizes weather radar calibration schemes, provides a reference base on radar calibration methods, and materially extends previous calibration studies. This report is a working document intended for the review and selection of WSR-88D calibration methods and for the development of selected methods.

This report is specific to the WSR-88D. It does not purport to solve the general weather radar calibration problem. It emphasizes the engineering basis of standards-traceable instrument calibration. Furthermore, its reasoning and recommendations are focused on intended feasibility for the WSR-88D network, with high marks for compatibility with network logistics, automation potential, clear-cut implementation and interfaces, and dual polarization sensing.

Recent experience has demonstrated that even with a built-in electronic "calibration-maintenance", WSR-88D radars can be out of calibration without generating alarms. Persistent biases in reflectivity among adjacent sites have been noted. The motivation to introduce alternate or redundant calibration methods into the WSR-88D network is high because of the important national priority of hydrology.

For this study, a calibration aid is an apparatus and a process that technicians and engineers use to verify and adjust the WSR-88D calibration state. An engineering calibration aid checks instrument calibration (software as well as hardware) by separating the instrument from variable off-site propagation and remote sensing effects (such as path attenuation and beam filling). Furthermore, an external calibration aid that is completely independent of system test signals can verify whole-system calibration including the internal electronic calibration-maintenance function. Independently traceable calibration aids generate confidence in the engineering calibration of the radar and provide a replacement engineering calibration in the event of system failure. The effectiveness of any calibration aid, whether internal or external, depends on careful analysis of system details, adherence to the initial engineering calibration state, and relevance of fundamental calibration standards.

For clarity this report divides the field of WSR-88D calibration aids into categories: "engineering" and "meteorological" and furthermore into "absolute" (basic) and "maintenance". The WSR-88D is a modern weather radar that employs built-in electronic "calibration-maintenance" to minimize field degradation from an initial "engineering calibration" state. Its intention is to remove temporal and environmental drift of the processing chain and to determine the existence of degraded or failed components. This built-in or internal calibration maintenance is accomplished through frequent, automated injection of test signals on the receive-side and on-line measurement power on the transmit-side. Not checked electronically are the antenna-radome and its associated transmission lines. This internal calibration-maintenance is based on an initial "engineering calibration", the term used to describe the measurement of individual losses and gains through which radar components are measured electrically by traceable means and then appropriately combined for a composite calibration. The WSR-88D operators presently have at their disposal an off-line, external but not independent, calibration aid known as "Sun Check". In this report, merits and difficulties with the WSR-88D Sun Check are briefly noted. In addition to the engineering aids there is a category of "meteorological calibration" aids that utilize comparisons among separate instruments or channels to deduce the reasonableness of the results on natural targets of opportunity.

The "market survey" conducted for this report reveraled no off-the-shelf calibration aid for weather radars. Though the principles for radar calibration were proposed in the early days of radar, and many ideas have been implemented on various systems, no directly applicable, integrated calibration aid was found. One reason may be that the implementation of an integrated calibration system, whether for a single radar or for a network, is highly system dependent and must be treated uniquely.

However, many calibration ideas that were impractical a decade ago are now feasible using commercial technological advances. Among new technologies, near field antenna measurements have been

commercialized, ultra-wideband waveforms offer promise for detailed path characterization, timekeeping improvements help synchronize active and passive radiometric transfer standards, laser trackers measure distances to a few parts-per-million, wideband telecommunications are cost-effective, improved processing and new process control strategies minimize calibration variation. Of necessity this report focuses on a handful of schemes that suggest most promise for cost-effective development and deployment. For example, this report discusses why a simple, active transponder is unlikely to result in reproducible calibrations for the WSR-88D network.

This report surveys a wide field of direct and auxiliary calibration techniques, from manual verification methods, to radar cross section measurements (including comparison of precipitation targets), to orbiting transponders, to channel sounding, to near-field antenna measurements, to improved radiometric techniques. For example, spherical projectiles could be dispensed or shot through the radar beam, sub-pulse coding could be applied for improved range discrimination, or a near-field device could be attached to the radome. Curious ideas with dubious practicality are also noted.

Calibration aids are then rated based on their usefulness to the WSR-88D. Of many schemes and variations considered, eight external calibration ideas passed the criteria for WSR-88D application based on their current status and possibilities for automation. The recommended methods in combination must be practical and provide field calibration of the following elements: (1) subsystem calibrations and an end-to-end reflectivity channel calibration, (2) antenna positioning variables at the base data output, and (3) stand-alone measurement of antenna patterns.

The following four calibration aids are recommended for near-term development and preliminary design. Costs for each are the subjects of study. Combined with an enhanced sun flux method, these recommendations constitute a robust suite of engineering calibration aids:

1. Calibration process-monitoring software
2. Independent radar test set method
3. Drifting sphere method
4. Near-field antenna pattern method

The radar test set provides a means for separate, traceable “engineering calibration”. The sphere is a fundamental, polarization-independent target for true “end-to-end” dual polarization radar calibration and it can be automated. In-situ spherical near-field methods claim to accomplish a dual-polarization antenna pattern measurement. These new methods complement an enhanced “Sun Check”. Troubleshooting becomes more efficient and more precise with multiple independent methods. Each recommendation embodies hardware, software and procedural elements as explained in this report, and directly supports both horizontal reflectivity and differential (dual polarization) reflectivity calibration. The development of process-monitoring software was judged fundamentally important to all calibration approaches. In contrast to “meteorological calibration” target comparison methods, technicians and engineers depend upon repeatable, specific, on-call procedures to precisely verify, and against which to adjust, instrument performance. Though engineers are skeptical of “fudge factors” to make a radar conform to its neighbors or to make data fit theory, “meteorological calibration” comparisons are indispensable to process monitoring of calibration and system degradation. It is the opinion of the authors that a test suite of automated calibration aids applied at different levels is needed for technicians and engineers to confidently verify and adjust WSR-88D network calibration.

At this writing, WSR-88D differential (dual polarization) reflectivity “engineering calibration”, “meteorological calibration”, and differential “calibration-maintenance” remain issues without consensus. A design-for-calibration approach minimizes the cost of hardware and software for improved primary calibration and for differential calibration that will be negligible compared to managing engineering change proposals later.

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1. Introduction

This study is founded on a "market survey" of radar calibration techniques. In brief, neither an off-the-shelf external "calibration aid", nor a simple configuration of test equipment, nor available calibration services quite fit the exacting WSR-88D calibration requirement. This finding is not surprising since exacting calibration depends on details of the radar's internal design and processing. The WSR-88D reflectivity uncertainty requirement exceeds the requirement for an air traffic control radar where calibration establishes system reference rather than target measurement.

Rather than the hoped-for, singular, off-the-shelf solution, the focus of this report is on potential improvements to calibration aids discussed in the Radar Calibration and Validation Specialty Meeting (Joe and Smith 2001) RADCAL 2001 conducted at the 81st Annual Meeting of the American Meteorological Society in Albuquerque, New Mexico. Not every conceivable radar calibration aid or radar calibration technique is described; many more were noted and are listed in the bibliography. At least one possible, cost-effective implementation of an idea was needed before selecting that idea for field applicability. The intention here was to propose ideas and techniques that can be developed in the near-term on the WSR-88D network.

The sources, large in number, are listed in the bibliography and in the commercial products list. The survey includes US government agencies, private laboratories, the university community, published engineering literature, the commercial sector, and the US Patent Office. Personal discussions are identified. It was necessary to apply selective criteria at the outset to filter low-probability-of-success ideas. For this filter we employed: (1) understanding of the WSR-88D network, technical and procedural; (2) understanding of recent technical advances that alter (usually improve) the feasibility of calibration ideas; (3) understanding of weather radar calibration gained by personal experience; and (4) by pointed discussion with radar scientists and radar engineers specifically for this report. By necessity, intuition plays in the selection process; there's no way out of it, but we hope it is intuition is based on practice. The experience and perspective of persons named in the acknowledgements was a prominent factor. Emphasis was placed on developing the techniques which will be of benefit to WSR-88D system upgrades, such as open-system processing and software upgrades, phase coding, dual polarization (Doviak and Zrnic 1998), and faster scanning. The evaluation criteria are described in a later section.

Commercial technical advances that we found most helpful are improvements in accuracy, communications, weight, and modulation capabilities of commercial test equipment. Others are the commercialization of near-field antenna measurements, commercialization of accurate GPS location and timekeeping receivers, laser trackers which measure distances to a few parts-per-million, advances in wireless data communications, and advances in automated test equipment. Through control of variation, manufacturers have improved their production processes and therefore the reproducibility of microwave components and test equipment over the last decade.

To implement a WSR-88D calibration aid the development must recognize critical procedures, system details, and software impact. For this purpose, development outlines are given with specific recommendations. After development, is it possible to have a calibration aid that dependably, cost-effectively, and reproducibly yields a sufficiently small standard deviation of instrument calibration across the network, say 0.5 dB, under given test conditions? Answers to this question became the main gauge for evaluating candidate ideas, as described in the evaluation criteria section later.

Calibration is occasionally judged "dull engineering", though among engineering activities it presents a large economy of scale. It is difficult to earmark sufficient funds for adequate calibration and calibration maintenance in an operating budget though it enhances product utility. Calibration recommendations at times are viewed as either inadequately compelling or too costly relative to the common benefit they provide. Also, calibration training is an important issue because field support levels increase interest in calibration and effectiveness.

A partial solution to scarce funding and scarce staff resources is advanced automation in data collection, which as a side benefit reduces calibration-process variance. Figure 1, intended to motivate funding for calibration, is from Pratte, Frush and Ferraro (1995), updated to 2003 dollars from 1983 dollars by the Bureau of Labor Statistics Consumer Price Index calculator, it suggests the economies of scale from improved calibration: the operational hydrologic benefit from improved measurement of precipitation reflectivity. The data and assumptions were taken from Hudlow, et al (1984). Estimating the economic benefit of instrument uncertainty (Taylor and Kuyatt 1994) depends upon the relative proportion of meteorology and propagation effects to instrument effects. A 1 dB standard instrument uncertainty was specified in the NEXRAD Technical Requirements (NTR, 1986). Based on experience and recent evidence, if the current standard uncertainty of reflectivity for the WSR-88D is deduced to be 2 dB (Sirmans 2004), and assuming an even split between meteorology/propagation and instrument, the annual benefit rate then follows the overall uncertainty from 2.8 dB to 2.2 dB, a benefit gain of $700 million per year. Proposed changes in radar sensing and signal processing (fast scanning) may reduce the meteorology/path uncertainty to the 1 dB level, boosting the implied benefit gain above 1 billion per year in 2003 dollars. This curve is not the cost of maintaining the radar calibration at the specified error, rather it is the annual hydrologic benefit derived from having a radar reflectivity known to the specified error.

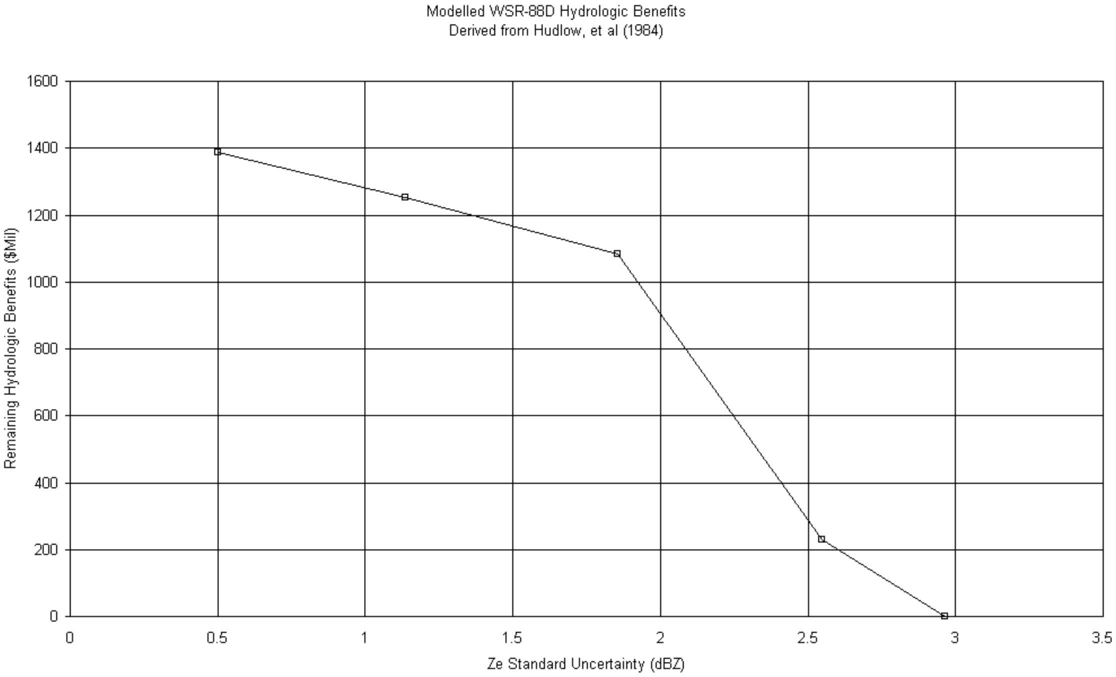

Figure 1 - Average Reflectivity Measurement Uncertainty translated into annual operational hydrology benefits (data and assumptions obtained from Hudlow 1984)

A few "soapbox" remarks about development are in order because there seems to be confusion surrounding WSR-88D calibration performance. Details of implementation, logistics, and execution can "make or break" a calibration. While a proposed calibration aid may be valid in concept, it is the implementation that results in an efficient, reproducible, cost-effective, low-uncertainty procedure. Techniques have received "bad press" (low community acceptance) because the implementation was "ahead of its time" and the developers could not field a practical product. Concepts have "good press" historically but a new implementation may contain procedural difficulties that render it sub-optimum. As always, there is the unavoidable "specsmanship" that needs to be discounted. For an engineering or meteorological calibration aid to be useful to large radar network, it must first and foremost be cost-effective. The selected calibration aids will need to withstand scrutiny from both radar specialists and government radar operations staff.

The concept and the practice of engineering reflectivity calibration are based on electronic and physical calibration practices. Smith (1968, 1974) defines the basic calibration concepts for weather radars. Sirmans (1992) applied the concepts to reflectivity calibration for the WSR-88D, developed an instrument uncertainty budget (Taylor and Kuyatt 1994), and recommended a supplementary end-to-end engineering calibration verification procedure (independent of the system's on-line calibration). Pratte, Frush and Ferraro (1995) presented a network-wide uncertainty budget and recommended automation, statistical process control, and a work plan for a WSR-88D calibration team.

The practice of engineering calibration on the WSR-88D is as follows: an initial "engineering calibration" of manual measurements of individual subsystems, and procedures for merging those in to a whole-system calibration establishes the calibration state of a radar. An automated engineering-calibration-maintenance (also known as electronic, internal or on-line) check is frequently run by injecting known signals into the waveguide at a common points, especially near the antenna, to simulate a received weather echo. Antenna/radome gain (which includes the remaining waveguide and the radome) and beam width are usually static quantities and are essentially derived or provided by the manufacturer. Average or peak transmitter power is measured at a suitable waveguide sensor. Injection points and sensed points are translated through measured transmission paths. Gain drifts in the receiver are calculated and removed. It is assumed, but not yet proven, that modern weather radars, including the WSR-88D, are inherently capable of maintaining an instrument measurement state (with dry radome) to 0.5 dB over the long term through an on-line, internal, electronic calibration maintenance aid.

1.1. Discussion of Issues

A standard definition for "calibrate" is to determine the response or reading of an instrument relative to series of known (radiation) values over the range of the instrument (IEEE 2000). Calibrating may also include adjusting a measuring instrument against a known standard, correlating readings of the instrument with a standard, testing a measuring device and then manipulating or changing its settings to conform to a chosen standard, thereby ensuring the device is working accurately.

The WSR-88D radar currently relies completely on the "internal" calibration-maintenance sources and processes to check the accuracy of its measurements. This electronic, internal calibration-maintenance process is distinguished from the basic "engineering calibration" of system components, as noted later. A partial exception to "internal" is Sun Check, a manual, off-line procedure that attempts to determine the composite gain from the open atmosphere to the antenna port injection point by referencing non-coherent solar power against the system gains, internal sources and solar flux measurements. However the current Sun Check is not independent of system signal sources and losses.

A variance study of the electronic and mechanical stability suggested that WSR-88D equipment (instrument) can be inherently calibrated to an "absolute" standard deviation of approximately 0.5 dB, and that the antenna-radome was the major unknown in the notional uncertainty of "end-to-end" calibration (Sirmans 1992). The antenna subsystem specifications were not routinely measured on site, but normally taken from the manufacturer. The "absolute" modifier requires that test equipment undergo rigorous calibration certification (traceability) and that a calibration verification be executed which may or may not be performed.

There are three notable issues regarding current WSR-88D engineering calibration and calibration-maintenance processes. First, with the internal closed-loop calibration-maintenance system, radars can still be out of calibration without generating alarms, as a recent experience at the Oklahoma City KTLX site confirms. KTLX appeared to be constantly 2 dB "hotter" than the surrounding sites, but was not generating calibration-consistency alarms. Second, radar system components outside the receiver test signal injection paths are not electronically or routinely checked. Third, the composite "engineering calibration", to which the internal calibration-maintenance is tied, may not be as accurate as desired. Clearly, there is an implied question of what is happening here?

A water-filmed radome is more attenuating than dry, and the variable attenuation condition, which in heavy rain events can exceed the reflectivity factor measurement accuracy requirement, will need to be compensated. (An example of rain attenuation during calibration is shown in Figure 10.) Manz (2001) summarized wet radome effects for RADCAL 2001. Sirmans (2004) contends that the impact of various off-site propagation and target-effects, plus the wet radome losses, and the planned WSR-88D upgrades, increases, rather than reduces, the necessity for better than 1 dB Ze measurement uncertainty.

Besides opinions from forecasters using the WSR-88D data, there have been multi-radar studies that suggest larger-than-desired biases in reflectivity factor across the WSR-88D network. These studies, which occasionally show intra-network differences of 3 dBZ, compare precipitation echoes. Results from these meteorological calibration aids are generally are better understood and thus preferred by meteorologists to engineering procedures. Emmanouil, et al (2000) used the orbiting Tropical Rainfall Measurement Mission (TRMM) precipitation radar (PR) as a transfer standard. Kozu et al (1994) outline the PR calibration procedure using an active radar calibrator (ARC). Bohlen and Chandrasekar (2000) also compare ground-based radars with the TRMM PR. Furthermore, Gourley et al (2000) report significant reflectivity differences among clusters of WSR-88Ds. Boustany (1999) completed a comparison between two WSR-88Ds in Florida. Though the comparisons have a high fluctuation level, similar results are identified in all these studies. While there may be engineering disagreement with their specific conclusions regarding the WSR-88D reflectivity calibration, the analyses seems to indicate that all ground based scanning radar systems are prone to a few decibels of reflectivity bias. This statement applies to both operational WSR-88Ds and calibrated research systems.

The multi-radar studies suggest an unanticipated behavior of measurement biases. If we assume that the radar instruments are themselves stable, then reflectivity differences ought to be systematic over long periods of comparison. However, the published difference data occasionally show abrupt changes for individual radars, more than experience with modern equipment would imply.

Recent experience hints that the WSR-88D as a fielded network may not meet the NTR 1 dB standard uncertainty of reflectivity measurement. The practice of 1 dB standard uncertainty in the field is a daunting challenge. And so is its verification, in the midst of the known issues beyond the antenna. Furthermore, if the 1 dB primary reflectivity calibration is regarded as daunting, consider calibrating the proposed dual polarization channels to 0.1 dB differential ratio, and maintaining the calibration over time, temperature, and signal magnitude.

Weather radar experience demonstrates that antenna-positioning errors have a tendency to increase in a scanning situation. Operational pedestal positioning inaccuracies can degrade the accuracy of the reflectivity field because of slew-rate-dependent biases in the bore sight angle assignment, elevation as well as azimuth. If at all possible, dynamic positioning accuracies should be verified by the selected external schemes.

1.2. Scope of report

This report comments on the feasibility of a wide range of weather radar calibration approaches and ideas ultimately recommending a specific small set for demonstration. This report addresses the question of how and which additional external calibration aids can be developed to verify WSR-88D network calibration consistency. It appears that some sites are being identified as out of agreement with adjacent sites for reasons that are unclear. To ensure the quality of data produced by the WSR-88D, and under guidance from the operating agencies, the Radar Operations Center (ROC) is committed to identify effective external calibration aids. Therefore, under direction from ROC Engineering we review availability and feasibility of equipment, software, and techniques that will measure the accuracy of any WSR-88D reflectivity data field by external means.

An engineering study/market survey of hardware and software for external calibration tests/verification is presented in this report, as are notional requirements for hardware, software and methodology to be used to conduct external calibration verification. The present effort revisits earlier studies to determine whether anything new might establish a superior calibration regimen. Selecting a specific external calibration device was not a fixed goal of the project, but specific recommendations are made. The emphasis of this report is what is termed here “engineering calibration”, but “meteorological calibration” aids are also considered.

The findings of this report directly support the ROC Engineering planning process. In a briefing to the WSR-88D Technical Advisory Committee the Operational Support Facility (OSF, the predecessor to the ROC) explained the development of calibration procedures up to that time, the WSR-88D calibration methodology, and progress (OSF 1997). These 1997 calibration plans are summarized below:

Short Term Plans

Operations and Engineering will continue to assist in correction of observed problems.
The OSF will assist in development of on site maintenance follow-on training similar to the distance learning capability available for operators.
OSF will incorporate into routine field procedures an "offline" comprehensive calibration verification (with minimum field staff impact).
OSF will expand and, eventually, incorporate routine monitoring and analysis of site performance and calibration parameters (all sites).
OSF will implement on-line calculation and display of reflectivity error estimate.

Long Term Plans

OSF will propose extending "sun scan" to include antenna main lobe pattern measurement.
OSF will investigate modification of on-line calibration routine from point check linear extrapolation over linear range to input/output regression over full dynamic range.
OSF will investigate tightening boundaries on calibration alarm monitoring.
OSF will study refinement of atmospheric loss correction routine.
OSF engineers will review code to identify changes that may increase precision.

Recommended external calibration options must be practical, cost-effective, and consistent with ROC plans. For the WSR-88D network consideration of system dependencies is imperative, dependencies such as logistics, interfaces, engineering change order processes, staff capabilities, automation opportunities, and so on.

1.3. Use of Terms

The following use of terms developed over the course of this study to clarify and categorize treatment of alternatives. These explanations are not definitions and the usage applies only for this report and for internal deliberations.

Calibration aids have been divided into two broad categories for this report. An “engineering calibration” for this report is a calibration method that is based upon standard procedures and sources that can be repeatedly calculated or traced to a national standards laboratory. Engineering calibration uses standard materials and processes to achieve the calibration state, always attempting to minimize undesired influence variables (side effects) during the calibration activity. Generally, the “absolute” or basic engineering calibrations require the instrument removed from operation for a short time.

A “meteorological calibration“ for this report refers to a calibration method that uses comparison of sensor data from meteorological targets. “Meteorological calibration” aids quantify reasonableness or representativeness of data by comparing readings from an instrument or channel being evaluated to those provided by another instrument or channel that is presumed to be operating properly. Sometimes translation algorithms, assumptions based on physical understanding, and ad hoc qualifiers are employed in these comparisons. Both phase and amplitude consistency criteria may be employed in the comparison. Translation between measurands, frequencies, and polarizations may be required. Because natural processes tend to be nonstationary and wideband, comparisons of this type are challenging. Meteorological calibration aids are intrinsically calibration maintenance activities, as they cannot achieve “absolute” calibration unless based on proven physical reasoning. Meteorological calibrations have been conducted both with the system in regular operation or in test mode. Good results from meteorological calibration aids build confidence in the user community.

Particular distinction should be noted between the terms “engineering calibration” and “calibration-maintenance” used in this report. An “engineering calibration” can come from installation (or re-installation) in which the individual subsystems or components are measured electrically and then appropriately combined for a composite calibration. It could be said that the WSR-88D was fully calibrated when the government accepted it. In the absence of a statistically significant number of calibration trials, or repeating the initial calibration a statistically significant number of times, an initial error could persist for a long time. Compare this with “calibration-maintenance” a set of activities carried on by staff and by the built-in test equipment, which modifies operational calibration and can affect calibration-related adaptation data. Calibration-maintenance of microwave circuits is a challenge because of the interaction of intended and unintended effects accumulating over weeks and months as units are swapped and measurements made. “Meteorological calibration” refers to a method or set of methods in which comparisons are made among spatially separate, and moderately independent, radars using similar natural unknown targets. Other “meteorological calibrations” employ consistency among natural target scattering and propagation modes using assumptions of orthogonal polarization.

“Internal” calibration implies an electronic calibration aid that is part of the online radar processing, also identified by the phrases “on-line”, “built-in test”, and “consistency-check”. “Calibration-maintenance” is the process whereby the calibration state is monitored and adjusted by internal means, that is, internal test equipment, usually to reduce drift between re-calibration cycles. It is part of the system design intended to minimize field degradation. But its use could be expanded to include calibration process monitoring and management.

“External” calibration means that the calibration aid is depends on a calibration standard outside the radar equipment (instrument) and separate from off-site propagation and remote sensing target effects. The standard may be on-site or it may be 800 km away. External calibration aids beneficially establish a statistical framework against which calibration maintenance can be made less frustrating and more efficient. Calibrating a weather radar on generated signals versus the intended pulse volume of individual precipitation scatterers raises debate that will be considered an off-site propagation and target issue.

“Automated” implies that a calibration measurement can be executed and the data logged with no or minimal staff resource. Calibration results obtained automatically may be analyzed “offline”.

“End-to-end” implies a calibration obtained with all subsystems in operational cascade. The compositing of individual component calibrations to produce the initial engineering calibration state of a radar system was the method used in originally in the WSR-88D. Without external checks, compositing can result in larger than desired “end-to-end” uncertainty. To be meaningful, “end-to-end” must clearly specify the input and output reference points.

Process improvement is the continuous investigation of hidden but correlated artifacts of a measurement and reducing them and reducing noise in the measurement. The goal is to continually decrease each error source to smaller and smaller percentage contributors (Montgomery 2004). Control of measurement process variation is the key to improvement. Both engineering and meteorological calibration aids are used in calibration process monitoring.

In general, the result of a measurement is only an approximation or estimate of the value of the specific quantity subject to measurement, that is, the measurand, and thus the result is complete only when accompanied by a quantitative statement of its uncertainty (Taylor and Kuyatt 1994). “Accuracy” is regarded as the closeness of agreement between the reading, which is a random variable, and the true value of a measurand. A "true" value is that value obtained by a perfect measurement and by nature is indeterminate. Accuracy is difficult to use, thus the standards bodies now use the term uncertainty to mean measurement uncertainty. The term “absolute”, when applied to calibration, suggests a derivation in the most basic manner from fundamental units of mass, length, and time measurement. Determining the "absolute" accuracy of a meteorological radar through an inter-comparison study is very difficult because there is no reference that can provide a known or true value of the meteorology and propagation. Uncertainties components are meteorological variability, spatial and temporal separation of the measurements, differential attenuation, polarization and wavelength effects, external and internal interference, random noise, and so on. Only "absolute" accuracy, in the sense of standards traceability, can be ascribed to the instrument by processing simulated signals. In assessing how well sensors compare, two measures are commonly used. These are the mean and the root-mean-square of a series of differences between two instruments measuring nearly the same population.

"Working standard" or check standard is a device routinely used to calibrate or check a measurement instrument. "Traceability" is the property whereby an unbroken chain of properly executed and documented comparisons exist between the instrument, the working standard, and a national standard.

"Independent" calibration methods imply separately traceable transfer as part of the calibration device or procedure. Independence is obtained by making sources and test equipment have a separate traceability route.

"Radar cross section" (RCS) of a target is also termed radar echoing area, assumed to be independent of interrogating signal amplitude. For backscatter it is formulated as 4π times the power returned per unit solid angle in the direction of the receiver divided by power per unit area as a plane wave incident on target. It is a property of the target influenced by radar wavelength, radar illumination function, polarization, and wave front properties. RCS is the aperture area which intercepts enough power from the transmit pulse to produce the received echo by isotropic scatter.

The term "background" usually means the measured RCS of the environment in the absence of the calibration target (Matyas and Kelsall 1991). Changes in temperature, noise figure, carrier frequency, instrumentation states, and arrangement of target suspension (Freeny 1965) and varying clutter in the main beam or side lobes may be related to changes in background signals. Additionally, interactions with the calibration target itself, its support, and other structures, such as multipath, are ultimately important. For this report "background" will imply all undesired signals of the active radar. For strong echoes post-detection signal to background (clutter plus interference plus multipath) should be very large so that individual uncertainty (Taylor and Kuyatt 1994) components are kept well under 1 dB. A maximum background E-field phasor addition error is approximately $20\log(1+E_{background}/E_{signal})$, so that a -30 dB field ratio yields a maximum error of 0.25 dB in power and 2 degrees in phase.

2. Introduction to WSR-88D Calibration

2.1. The reflectivity measurement

Discussions in this section support the development of weather radar calibration by external targets and radio frequency sources. Deviations from ideality are often the source of measurement difficulties. Several of these deviations are discussed or implied in the following sections. External calibration targets and sources are vital to verify end-to-end calibration consistency, because the scattering and signal behavior of external targets can be controlled to a much better degree than natural targets.

Received Echo Waveform

The received waveform from a target is modeled with undesired signals in the following. Given constant transmit power and a stable system gain, received power is a random variable converted to reflectivity. Received power is calculated from the square of the waveform voltage sweep V(t) a function of time for a selected polarization (Doviak and Zrnic 1984).

$$V(t) = \alpha \exp(j2\pi f(t - 2R_1 / c) + j\phi)W_1(t - 2R_1 / c) +$$
$$\beta \exp(j2\pi f(t - 2R_2 / c) + j\psi)W_2(t - 2R_2 / c) + n(t) + i(t) + b(t)$$

The first term is the echo of the desired target at path range R_1 magnitude α, and phase offset ϕ, a function of transmitter power, antenna pattern, range, pulse range weighting, other system losses, bandwidth, path losses, and target RCS at the given angles and polarization. The round trip path length is 2 R_1, and 2 R_1 /c is the round trip delay, where c is the wave speed. The weighting function W illustrates the effect of antenna pattern, pulse range weighting, and bandwidth by the when t is within ($2R/c < t < 2R/c + PW$) where PW = cτ is the RF pulse length. Pulse length is occasionally replaced by the instantaneous receiver illumination h = cτ/2. The total phase of the desired echo is a function of time, range, propagation offsets and backscatter phase ϕ. Complicating signals arise in the measurement environment. This term is followed by a term due to a second arrival at path range R_2 and offset phase ψ, where the coefficient β depends on different reflection (scattering) factors and perhaps nonlinear factors. R_1 and R_2 are close but not identical. Background signals b(t), thermal noise n(t), and interference i(t) are uncorrelated from the radar echo in many cases.

Radar Cross Section (RCS)

The radar cross section (RCS), usually represented by symbol σ, of a point target is 4π times the ratio of backscattered power S_b per unit solid angle to the incident power S_i per unit area in a uniform plane wave at the target (Skolnik, 1991). Received power P_r and transmitted power P_t, each normalized by appropriate solid angles in the far-field (as R becomes large) gives RCS in units of area. Though this definition assumes that the target scatters energy uniformly in all directions, power scattered in forward directions may not be uniform and is not normally a contributor to RCS calibration of a monostatic radar.

$$RCS = \sigma = 4\pi R^2 \left(\frac{S_i}{S_b} \right) = 4\pi \left(\frac{P_r}{4\pi} \right) / \left(\frac{P_t}{4\pi R^2} \right)$$

RCS Measurement

To the certainty that the factors on the right hand side of the equation below are known, an aspect-dependent RCS is measured by evaluating the point target monostatic radar equation (Skolnik 2002).

$$RCS = \sigma = \frac{64\pi^3 R^4 P_r}{\lambda^2 P_t G^2 L_p}$$

Radar targets are assigned an RCS in meters squared, which is proportional to received power Pr, and range R^4, inverse transmit power P_t, inverse antenna gain G^2, and inverse wavelength squared, and inverse excess path attenuation L_p.

Volume Reflectivity

The focus of this report is the meteorological radar cross section measurement, the “volume reflectivity” η (m^2/m^3), the zeroth moment of the received echo spectrum, expressed as the “effective weather radar reflectivity factor” Z_e in mm^6/m^3 (Skolnik 2002). The volume reflectivity measurement is essentially an estimate from a random process, a radar cross-section measurement averaged from individual sweep(s), over the range cell(s) (precipitation volumes), the pedestal azimuth(s) and elevation angle(s), over particle(s), and using an instrument conversion factor, the so-called “radar constant”, which depends on the operating wavelength of the radar, the shape of the transmit pulse, and the shape and gain of the antenna pattern. "Effective" or "equivalent" reflectivity implies a reflectivity calculation, which contains assumptions that may not be valid, assumptions such as a fixed Gaussian antenna pattern, Rayleigh scattering, and a dielectric constant of liquid water (Probert-Jones 1962). By virtue of the assumed Rayleigh scattering regime in the "pulse volume" Δ, effective reflectivity Z_e in meteorological units (mm^6/m^3), or in conventional units (m^6/m^3), is proportional to the sum of the sixth-power droplet (sphere) diameters D_i, conventionally specified in millimeters, heavily weighting the large droplets.

$$Z_e = \Sigma D_i / \Delta$$

The internal motions of the spherical droplets within Δ constitute target fluctuations, or noise of measurement.

RCS of Meteorological Volume Target

The RCS of a volume target is an averaged quantity (over volume and usually over time) obtained as volume reflectivity η, related to Z_e through normalizing factors that assume that water droplets are small and spherical relative to the radar wavelength (Rayleigh scattering).

$$RCS = \sigma = \eta\Delta$$
$$\eta = \pi^5 \mid K \mid^2 \; Z_e / \lambda^4$$

The pulse volume Δ is rarely incremental or small (uniform illumination of the spheres) but rather a large effective pulse volume with varying illumination. With an assumed circular Gaussian antenna pattern the following approximates the pulse volume.

$$\Delta = \pi R^2 \theta^2 h / \left(8 \ln(2)\right)$$

The complex index of refraction of the dielectric to background is n, which magnitude varies largely with wavelength and temperature. For water |n| is approximately 9 at 3 GHz and falls to approximately 4 at 40 GHz at 273K. $|K|^2$ relates the complex index of refraction of water spheres to the form used in the RCS and is often taken as 0.93 in the weather radar equation.

$$\mid K \mid^2 = \mid \left(n^2 - 1\right) / \left(n^2 + 2\right) \mid^2$$

Weather Radar Equation

The logarithmic form of the radar equation (Doviak and Zrnic 1984) best illustrates that to measure calibrated reflectivity Z_e, the received power P_r, the range R, the azimuth and elevation angles Az and El, the excess propagation path loss L_p, and the instrumentation quantities, such as pulse width and antenna beam width need to be well known. Many of these quantities are terms in the so-called "radar constant" C:

$$Z_e\,(Az, El, R)(dBZ) = 10log(P_r) + 20log(R) - 10log(L_p) + 10log(C)\ .$$

In any given implementation, the radar constant C can contain slowly varying quantities, such as receiver conversion gain, system and site losses, and "hidden" assumptions. In WSR-88D software jargon the radar constant derived from the engineering calibration is called "SYSCAL" (Sirmans 1992), and temporal variations obtained by the internal, electronic calibration-maintenance function software is called "delta SYSCAL" or "CAL#"

$$dBZ_e(Az, El, R) = 10log(P_r) + 20log(R) + R*Atmos + SYSCAL + CAL\#$$

where Atmos is the atmospheric loss in dB/km (generally very small for the 10 cm WSR-88D wavelength except in heavy precipitation).

RCS of Calibration Targets

The maximum backscatter RCS of a conducting (metallic) sphere whose circumference is much larger than the wavelength (optical approximation) is simply the geometric cross section

$$RCS = \sigma = \pi D^2 / 4 .$$

The large conductive sphere has a backscatter efficiency of unity relative to isotropic, whereas large dielectric spheres selectively backscatter scatter with efficiencies greater than unity, i.e., larger than their physical cross section as described by Atlas and Glover (1962) and Probert-Jones (1962).

For a single conductive (metallic) sphere whose circumference is much smaller (Rayleigh approximation) than the wavelength (Ulaby et al 1981)

$$RCS = \sigma = 144\pi^5 \left(D/2\right)^6 / \lambda^4 = 2.25\pi^5 D^6 / \lambda^4 .$$

For a single homogeneous dielectric sphere whose circumference is much smaller (Rayleigh approximation) than the wavelength (Ulaby et al 1981)

$$RCS = \sigma = 64\pi^5 \left|K\right|^2 \left(D/2\right)^6 / \lambda^4 = \pi^5 \left|K\right|^2 D^6 / \lambda^4 .$$

In Table 1 we compare three targets that have been proposed at various times for weather radar calibration. At 10 cm wavelength, a single 6mm metal BB has a Rayleigh RCS of approximately 3 x 10^{-7} m^2 or 3 x 10^{-3} cm^2. Compare this with the measured cross section of a medium insect (worker bee) inferred from X-band to S-band as 5 x 10^{-3} cm^2. The conductive table tennis ball backscatters in the Mie or resonance region at S-band. A 12” diameter conductive sphere has an optical RCS of approximately 0.075 m^2 or 750 cm^2, several times larger than measured cross section of an average bird of 0.01 m^2.

Sphere	**Diameter**	**Approximation**	**Reflectivity**
Raindrop	2 mm	Rayleigh	-45 dBZ
Metal BB	6 mm	Rayleigh	-12 dBZ
Conductive Table Tennis Ball	40 mm	Mie	30 dBZ
12" Conductive Sphere	305 mm	Optical	42 dBZ

Table 1 - Approximate S-band (wavelength 0.1 m) reflectivity at 10 km from single spheres suggested for weather radar calibration.

The maximum RCS of a large conductive triangular trihedral reflector, where A the length of a triangle face edge, is

$$RCS = \sigma = 4\pi A^4 / \left(3\lambda^2\right) .$$

For a given size, the triangular trihedral generally yields a greater maximum RCS, whereas the sphere’s RCS is less sensitive to wavelength variations.

A rectangular flat plate at normal incidence yields a maximum RCS considerably larger than a sphere, where A and B are the lengths of each side

$$RCS = \sigma = 4\pi A^2 B^2 / \lambda^2 \ .$$

The RCS of an active radar calibrator (ARC, transponder) can be calculated from the effective transmit G_t and receive G_r aperture specification and the tandem internal gain (or loss) G_i of the ARC

$$RCS = G_t G_r G_i \lambda^2 / (4\pi) \ .$$

2.2. Practice of WSR-88D Reflectivity Calibration

The WSR-88D engineering-calibration-maintenance processes, part of the built in test equipment (BITE) consistency-checks is intended to operate as follows. Internal signal sources and a power sensor are established by transfer of calibration through standard test equipment maintained to a given calibration uncertainty level through traceable procedures. These are then translated to reference points by sums of loss factors contained in the adaptation data tables derived from an engineering calibration, effectively producing a set of test signals to check receiver paths. The reflectivity Z_e of the test signals are calculated and compared to expected values.

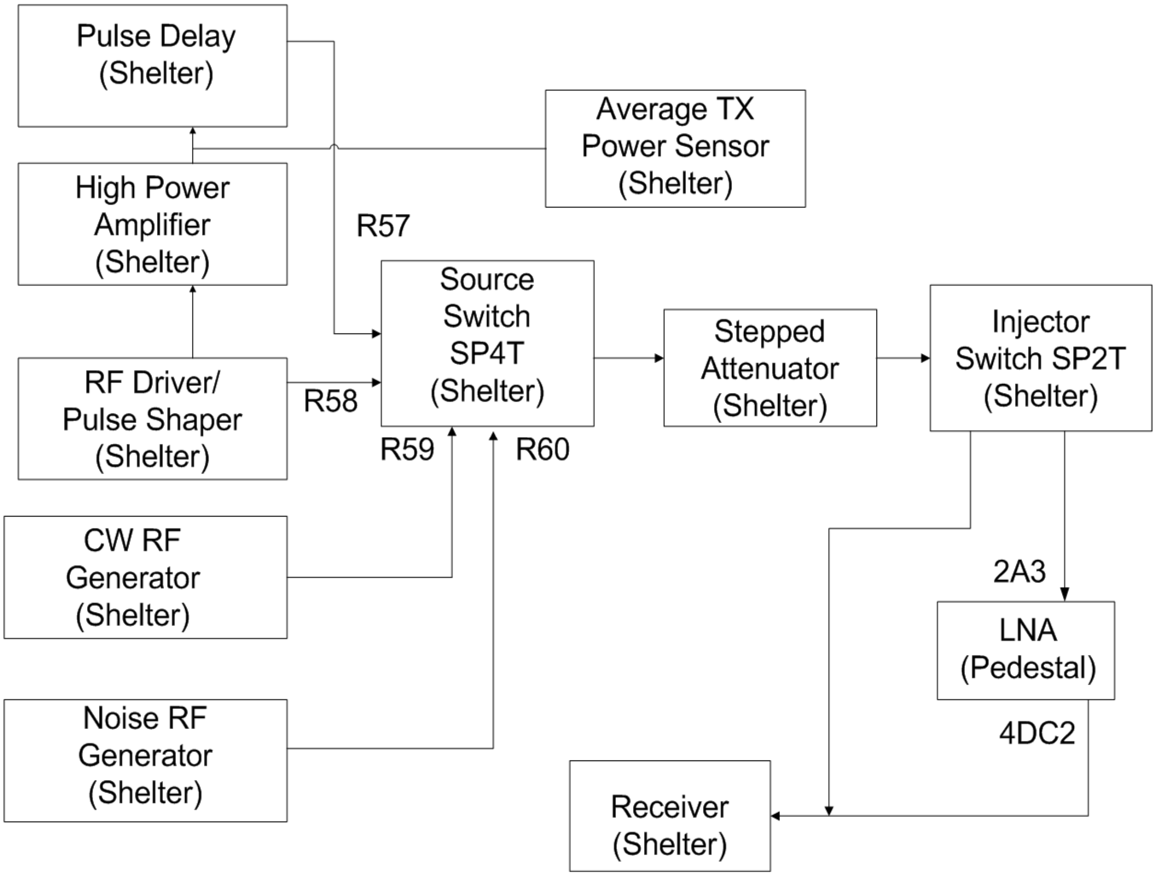

Figure 2 - Simplified Diagram of WSR-88D Electronic Calibration-Maintenance

In WSR-88D calibration jargon, the so-called “critical path” is a set of switched test signal paths whereby the CW RF Generator (R59), the High ENR Noise Source (R60), the RF pulse Shaper/Driver (R58), and the Delayed Klystron Sample (R57), can be selectively switched into the receiver at either the LNA input coupler located inside the Receiver Protector (2A3) in the pedestal or switched into the RF cabinet input (4DC2) in the shelter, illustrated in Figure 2. It is intended that four now-calibrated signal sources, a four-position switch, one stepped attenuator, a two-position switch, short cable jumpers, and the long waveguide run to the “front end injection” port provide the test signals. For each of the four test signals either “LNA front-end injection” or “receiver cabinet injection” is possible. Software controls the switches and algorithms “cross-check” the signal consistency and form gain correction factors from the receiver responses to the four types of inputs, from the measured average transmit power, and from static operating variables. Reflectivity calibration depends inexorably on the processor (software) having knowledge of the calculated test signal level, for example at the end of the path from the CW RF generator (R59) through the Receiver-Protector coupler (2A3).

Present software controls two variants of calibration checks. In the interval between Volume Coverage Patterns (VCP) the CW RF Generator and the RF Pulse Shaper/Driver are injected into the LNA coupler at several ranges (sweep times) and power levels. Every 8 hours a Delayed Klystron Sample is also injected. However, not every combination of signals or possible injection levels is used in each consistency-check algorithm, nor are intermediate results logged.

The so-called “shared path” (shared between test target processing and weather processing) in the receiver chain consists of the circulator, the T/R limiter, the LNA, the long receiver tower-waveguide, and the remainder of the receiver and signal processor.

The antenna main beam gain calibration concept is as follows. The intended default gain is calculated from a set of standard gain formulas. To calibrate the antenna that is part of an assembled radar set is to compare its performance against a standard gain antenna using a test method, and use the appropriate propagation formula. The WSR-88D procedures attempt a solar flux transfer method to refine the default antenna gain. The measurements are equivalently called “gain-transfer” or “gain-comparison”. The methods require the use of a standard gain antenna against which the antenna-under-test (AUT) is compared. WSR-88D antenna gain is actually net antenna gain subject to the transmission line to the antenna reference port, subject to mismatch losses and subject to the orientation of the antenna with respect to local structures.

The IEEE Standard Test Procedures for Antennas (1979) describes antenna gain measurement methods. On an antenna measurement range the antenna under test (AUT) may be compared to a pyramidal horn, as at the manufacturer’s plant. On the radar measurement range, the AUT is measured by echo received from a calibration target (a standard gain antenna) of known cross section, such as a metallic sphere or trihedral reflector. Alternately, in the solar flux transfer methods the gain of the AUT is compared to the gain of the calibrated solar flux antenna of the solar observatory, premised on the uncertainty of the engineering calibration of the WSR-88D and practices of the solar observatory. In practice, to produce results reproducible at the sub-dB level from either method, extreme care and understanding is exercised in test setup and execution. Automated measurements, with supporting data, are preferred over manually conducted experiments.

Process monitoring for the WSR-88D calibration was not provided by the manufacturer, not were tools to manage calibration (adaptation data) across the network. As with other complex instruments, the calibration state of a WSR-88D (adaptable parameters, etc) should never be altered based on a single calibration measurement. Experimental error is distinguished from the underlying calibration state of the radar using formalized process control techniques (Montgomery 2004; Hughes, et al 2002). Calibration-specific automation enhances field staff effectiveness to manage calibration-related work.

3. Relevant Calibration Work

The engineering study/market survey for this report includes published literature, industry, academia, commercial sector, and activities of government agencies. This report section also updates the earlier work on the categories of calibration options (Sirmans 1992; Pratte, Frush and Ferraro 1995; Sirmans and Urell 2001).

3.1. General Discussion of Calibration Transfer Using External Targets

Supporting the following general discussion of ideas for calibration aids is an institutional experience base. The weather radar research community continues to employ a variety of engineering and meteorological calibration aids, evidenced by papers presented at the RADCAL 2001 workshop. About 10 years ago the NCAR/ATD Remote Sensing Facility staff, experienced with solar flux techniques, standard gain horn methods, and tethered spheres, compared various external calibration schemes. These schemes include lunar radiometric transfer, Cassiopeia-A radiometric transfer, lunar reflection, low earth orbit calibration sphere tracking, and airborne calibration spheres, using the NEXRAD prototype “Mile High Radar”. Several of these techniques are currently employed on the CSU-CHILL and the NCAR S-PolKa radars. Based on that experience with weather radar systems similar to the WSR-88D, we propose several promising ideas after this general discussion of techniques.

Historically, calibrations by committed, knowledgeable radar staff have been good, but the superposition of small effects from a variety of measurements seems to place limits on the achieved result. Subtle errors creep into the measurement chain from secondary deficiencies in test equipment, adaptors, cables, equipment mismatches, and attenuators. Calibration procedures and algorithms may have logical flaws. A tenet of engineering calibration is that calibration in sections should "sum" to a complete and unambiguous calibration of a system. Though a given S-band measurement might be repeated to a tenth of a dB on the bench, comparison of different methods at different sites, but different staff disclose reproduction variations on the order of 3 dB, suggesting that the above basic tenet may not be directly extended to this practice. In working toward a reproducible and practical calibration aid for the WSR-88D, description of the following subjects follows: Traceability, Solar and Celestial Radiative Flux Transfer Methods, Radar Calibration Targets, Lunar Reflectivity, Transponder Methods, Elevated Ground-range Methods, Near-Field Measurements, Multi-radar Comparison Methods, Rain Gauge Methods, and Dual Polarization Methods. These descriptions cover useful external engineering and meteorological calibration approaches.

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3.1.1. Traceability

The traceable calibration is the basis for an engineering calibration. Two nonexclusive approaches have been discussed regarding standards traceability and reflectivity uncertainty over large geographic regions. Their practicality is a continued subject of discussion. The ‘traveling standard approach’ brings sites into conformance by applying standards traceability according to the basic engineering calibration tenet. This is the approach currently practiced for the WSR-88D. In the ‘master site approach’ an attempt is made to authenticate the calibration of one selected site, and then propagate the comparison check by independent, reproducible, external means. This approach is less common and may be more complicated. Perhaps a combination of both may be most cost-effective, and the WSR-88D program appears headed for a combination by virtue of this report.

External transmit/receive calibration aids combined with methods for process monitoring of calibration data and tracking system changes, yield a check on system gains, antenna gains, and pointing accuracy. Development of external targets needs attention to the environment and to reduction of variance, or the practical contribution will be minimal.

3.1.2. Solar and Celestial Radiative Flux Transfer Methods

Solar flux measurements have been extensively used for engineering calibration of gain and boresight alignment of large antennas for which no other means were available. The measurements also have been used to monitor receiver figures of merit. The sun represents a target for routine comparison checks of system gain and pedestal pointing alignment because of its high signal to noise ratio. However, the sun is a highly variable, unknown radio source of large angular diameter. For best performance, solar observatory reports must be quality controlled before use in these methods and deconvolution of the source function must be carried out. Explanation of solar flux transfer (SFT) methods, recommended practices, and details for enhancing the WSR-88D flux transfer implementation are presented in earlier reports (Whiton, et al. 1977, Frush 1984, and Pratte and Ferraro 1989). Modern pedestal control, data communications, and processing make it possible to automate the solar flux measurement. Questions that pertain to the WSR-88D solar flux transfer implementations:

1. Does the flux transfer implementation perform correctly and consistently in detail?
2. Can the implementation been independently verified against stable celestial radiometric sources, such as Cassiopeia-A and the moon?
3. Can we quantify reproducibility under varying solar, environmental, and local conditions?
4. Was the solar source a uniform emitter at the time of baseline measurements?
5. Can we infer the closeness to an "absolute" gain measurement?
6. Does the available solar observatory data need preprocessing?
7. Can we use the measurements in dual polarization feed horn alignment and differential gain assessment?
8. Can we use the measurements for radome wetting and aging assessment?
9. Can we quality control the results in a manner that reveals network calibration compliance?
10. Are intermediate measured/calculated quantities available for offline analysis?

A solar flux transfer implementation is a radiometric measurement using an unknown and highly variable, but common source. If the measurements are simultaneous and variance is controlled, the technique can give consistent pedestal positioning checks, receiver noise figure and bandwidth, and one-way main beam width, and the gain/temperature (G/T) figure of merit. Measurement of side lobe levels is possible with a single receiver, however low SNR increases the error and the extended source results in smearing. The solar flux transfer method works by matching, or transferring, the unknown gain of the WSR-88D antenna to the gain of a "standard" antenna used at the solar observatory. Error control to the sub-dB level relies on use of proper technique, automation, knowledge of observatory practices and data, and simultaneous measurements. Observatories provide a multiple measurements of received power through their antenna, customized for solar physics and solar weather applications. In Figure 3 an impression of solar measurement variability can be formed. The standard deviation of spot values of Penticton flux compared to Penticton (PEN) daily average was 0.06 dB. Average daily PEN flux is plotted as a ratio of “quiet sun” flux, 10log(S/80), where S is expressed in solar flux units (1 SFU = 10^{-22} W/m^2/Hz). Other solar patrol reports relative to the daily PEN average exhibited the following relative standard deviations (SD): SD(SAG) = 0.53 dB, SD(PAL) = 0.20 dB, SD(LEA)=0.28 dB. For comparison, a temporal offset of one day in Penticton flux results in SD (PEN) = 0.20 dB relative to the daily PEN average.

Puhakka et al (2004) present recent experience using the sun to obtain antenna parameters of a weather radar. Our experience with the celestial radio sources suggests that careful manual application of solar flux observations by practiced staff yields antenna main beam gain repeatability of approximately 0.5 dB. Solar flux measurement programs on the NCAR Mile High Radar, the NCAR S-PolKa, the CSU-CHILL, and National Severe Storms Laboratory (NSSL) Doppler weather radars support this “rule of thumb”. The well-behaved sequence of results proceeds from controlling variation during “offline” processing of repeated radar measurements and editing solar flux reports.

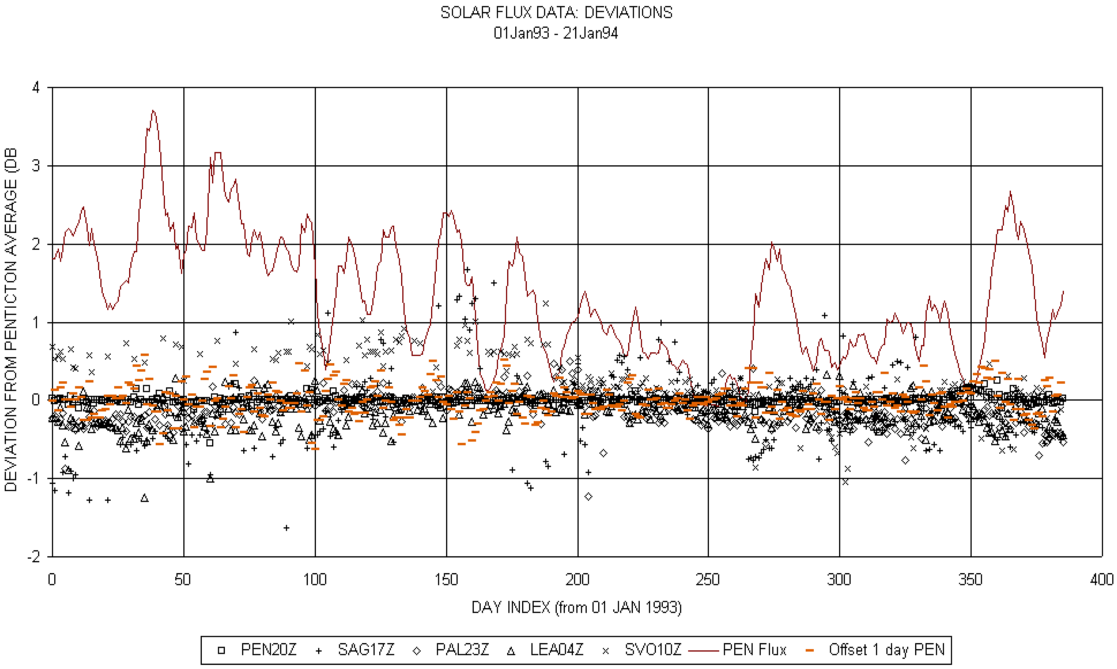

Figure 3 - Observed S-band Solar Flux Variations from 1993 and Jan 1994. This period was a quiet solar interval.

3.1.3. Radar Calibration Targets

Reflective calibration targets used for external engineering calibrations include flat plates, cylinders, dihedral and trihedral reflectors, and standard gain horns. Of these, spheres are omni-directional targets that have been used in radar calibrations since the 1940s, mounted on pylons, tethered, free-floating, fired from cannon, or in orbit. Under optimum conditions the simple target with calculable electromagnetic properties can provide an end-to-end check of the WSR-88D, which includes two-way antenna pattern out to second sidelobe, the transmitter, the receiver/signal processor, and the interfaces. The mathematically calculable target is fundamentally a type of antenna comparison method.

The usefulness of the sphere as polarization-independent calibration arises because its radar cross section does not depend on aspect and it may be calculated to sufficient certainty from fundamental electromagnetic theory. The RCS of an ideal conducting sphere of given diameter may be calculated using the Mie method. Though low, scattering efficiency is adequate for reasonable sized spheres on terrestrial radar ranges. A major advantage of the sphere is that the return echo is identical to the transmitted pulse, appearing at the two-way range delay of the sphere.

Experiments at the Mile High Radar and CSU-CHILL suggested that a usable, dual-polar antenna pattern could be derived from the sphere echo data set. Figures 4 through 6 illustrate attempts using a sphere technique on weather radars similar to the WSR-88D. Figure 4 shows received echo power from a 7” sphere acquired by coarse scanning across the unknown balloon trajectory contains system noise, echo return through antenna sidelobes, and range sidelobe return. The large “downside” spread of received power corresponds to poor main-beam-to-target tracking. In Figure 5 the strongest 6 dB returns at each range cell are retained. An inverse range to the fourth power line is "fit" along the strongest power values.

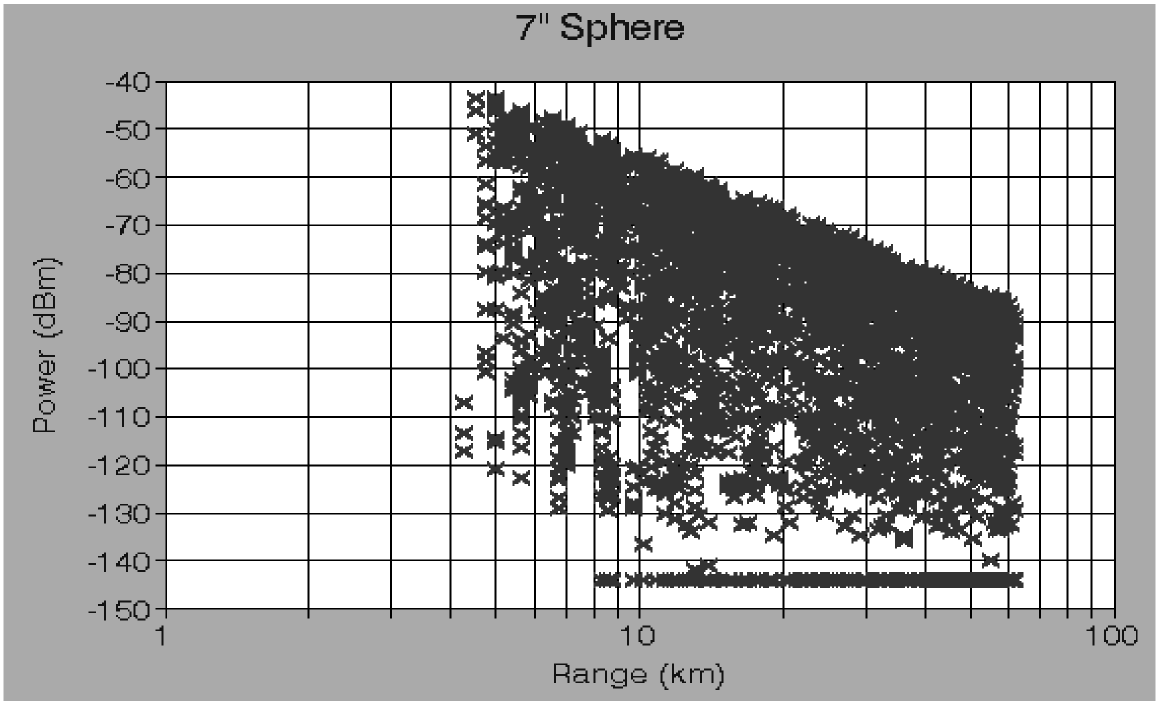

Figure 4 – Received Power from Box-Scan of Drifting Sphere (Mile High Radar, 30 August 1994 flight) indicating varying return from main beam and sidelobes with mean thermal noise subtracted.

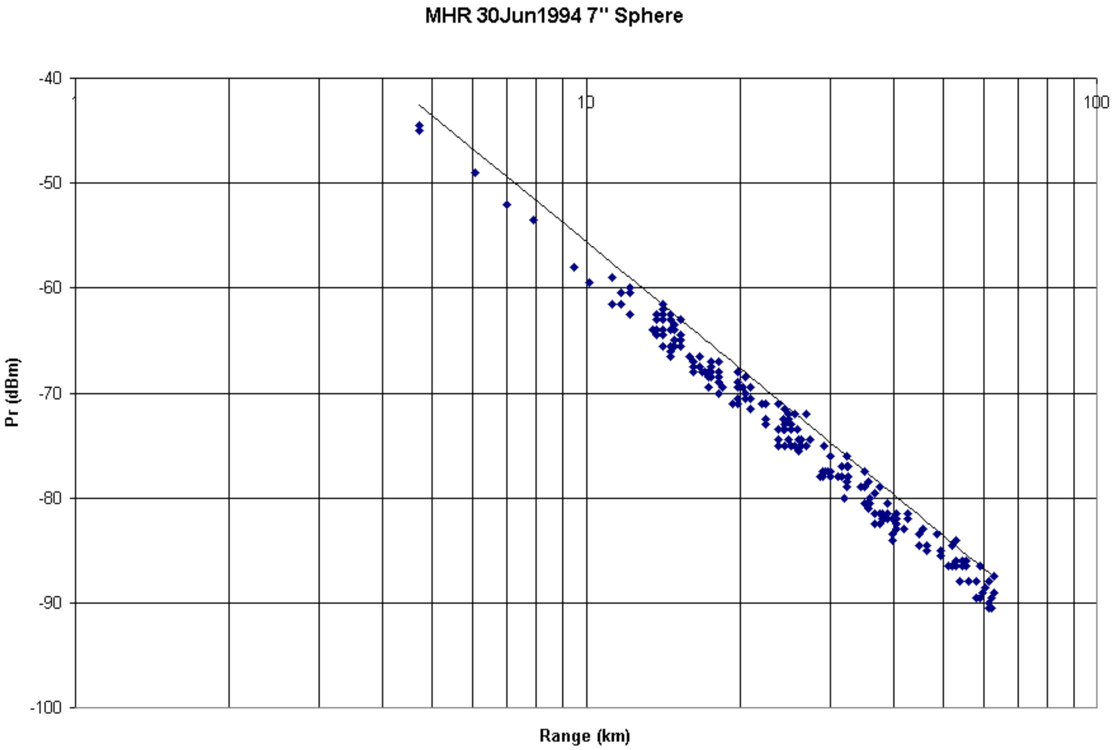

Figure 5 – Scatter diagram of the highest 6 dB received power at each range (Mile High Radar, 30 June 1994 drifting sphere flight).

Though articles have been published over the years on metallic and dielectric spheres for radar calibration, funding and practical issues have not pushed development toward routine and widespread use. There are practical matters to deal with. The echo from spheres suspended near the ground is usually buried in clutter and multipath. Aircraft towing is costly and may not be possible near certain WSR-88D's. Tethered-balloon spheres are a compromise but require far-field real estate (> 2 km) and hours of setup time. Attempts at balloon-borne, free-floating, drifting spheres as a weather radar calibration aid have been generally more successful.

The drifting-sphere method, practiced most recently at Colorado State University, is briefly discussed by Pratte, Frush, and Ferraro (1995) and further by Brunkow (2001). Zrnic et al (1987) reported tracking reflective balloons by NEXRAD for the purposes of defining the large-scale wind field. In the experiments at Mile High Radar and at the CSU-CHILL radar a track-while-scan (TWS) algorithm was used to acquire the data shown in the figures. Figure 6 depicts the occurrence distribution of CSU-CHILL "system gains" in July 2000 calculated from drifting sphere returns. The distribution shows a sharp drop at the system gain of 42.7 dB. Figure 7 shows the release of a calibration sphere during an undergraduate experiment. The initial efforts suggest that drifting-sphere acquisition, tracking, ranging, and cost can be optimized and that successful 2-way calibrations are feasible.

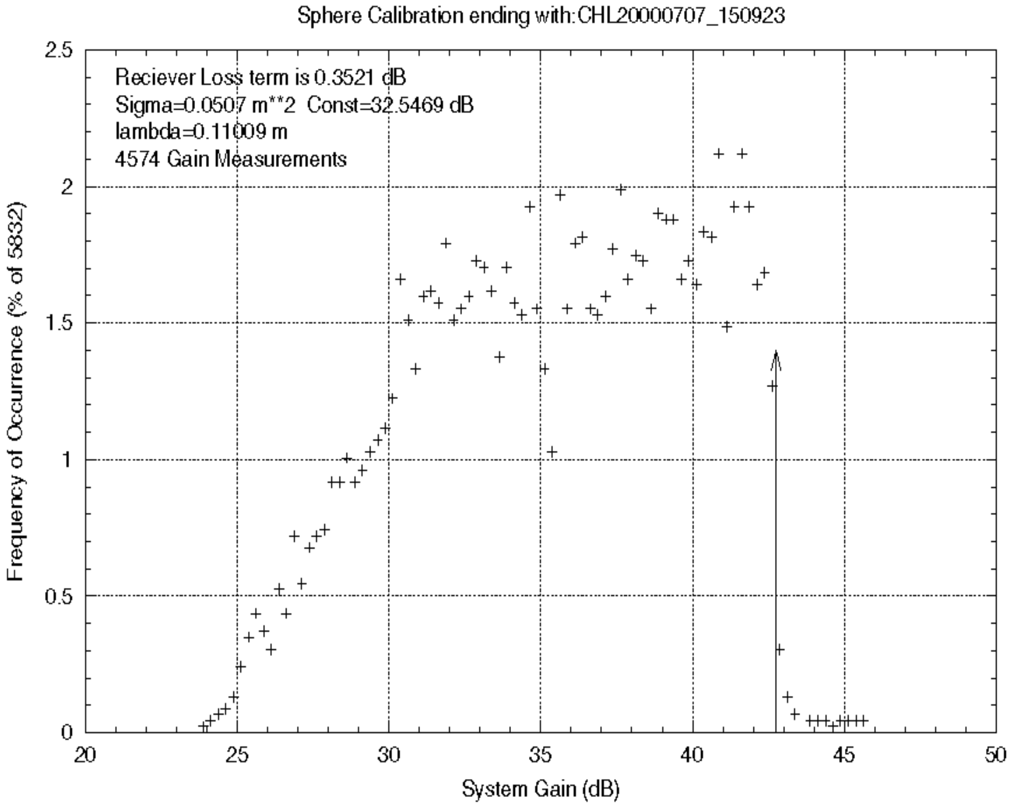

Figure 6 - CSU-CHILL System Gains Calculated from Echo Power while scanning across a drifting radar calibration sphere (Brunkow 2001).

Figure 7 - Release of Radar Calibration Sphere from CSU-CHILL (Brunkow 2004)

Characterizing the “background” for the supporting balloon and tether is important for RCS measurement. Additionally, the perfection of the sphere is an issue. Burrows (1968) develops a rationale for handling mechanical irregularities and Kent (2001) implies that a specification for radar calibration spheres is a maximum eccentricity of 0.5%.

Using calibration spheres in low earth orbit seemed custom-made for the weather radar application. In 1994 NASA supported a project called Orbital Debris Radar Calibration Spheres (ODERACS) from the Space Shuttle. However, calculations and engineering experiments with the MHR indicated that their usefulness was limited because of difficulty in obtaining sufficient post-detection SNR to make a good measurement of cross section. The principal obstacle is obtaining sufficient dwell time on a fast-moving spherical target even when angles and range are precisely known. The current WSR-88D limitation of 60 degrees elevation angle removes access to the strongest part of many orbital passes. Tracking of satellites and measurement of their RCS was tested in 1995 with MHR. Attempted were Object 21190, Cosmos 2137, Object 5398, Gridsphere 1, Object 16609, and the Mir station. Tracking was relatively straightforward using ephemeris predictions and pedestal positioning software. Unfortunately, orbiting objects with adequately high signal-to-noise ratios also exhibited unstable RCS due their complex structure.

There appear to be several specialized calibration targets worth reporting. Bruder, J. A. (1992) has invented a broad-beam diplane reflector (“bruderhedral”) with high polarization purity that could be employed on a properly conditioned antenna measurement range. Gillard and Whiting (1978) invented a pseudo-trihedral calibration reflector using the earth’s surface as one reflector plane, presumably eliminating ground distortion. We could find no performance results for this reflector. Souyris, et al (1995) synthesize an optimal, shaped dihedral with wide angle, low cross-polar backscatter. Atlas (1966) devised a fixed, large-RCS, lens-type reflector that could be employed for weather radar calibration on a radar measurement range. Martner et al (2003) describe results from calibrating a millimeter wave radar using a fixed trihedral reflector on a tall wooden pole, in a band where the far-field is closer and target to background ratio can be better managed. Silverstein (1997) evaluates bruderhedrals as calibration targets at millimeter wavelengths. Robertson (1947) describes an interesting bi-conical dihedral, among radar target options. Muth et al (2003) describe calibration of polarimetric radars using dihedral reflectors. Klugman and Stephan (2004) describe a rotating corner reflector application. Except when the echo can be raised out of the background, the utility of reflective targets is severely limited by multipath as discussed later.

3.1.4. Lunar Reflectivity

The largest “calibration sphere” is the moon. Use of the moon in engineering calibration of large radars must be as a transfer target because the moon’s backscatter cross section cannot be calculated from theory. Astronomy radars have measured the RCS at various frequencies and orbital positions (Evans and Hagfors 1968), but the published RCS is not reliable enough for WSR-88D, so the moon must be considered an unknown target. Its radar cross section appears to be sufficiently large and stable that a calibration scheme could be developed for the WSR-88D. Lunar echo can provides an end-to-end check of the radar (two-way main beam gain, transmitter, receiver/signal processor, base data system, and pedestal positioning accuracy). The moon is available to all sites worldwide, for angles that are well off the horizon, and its position in angle and range is as predictable as the sun. Lunar observations by radar reached their prime in the early 1960s, and are well summarized by Evans and Hagfors (1968). Pratte et al (1995) provide material to develop an active lunar calibration aid for a weather radar network.

The moon is a quasi-specular target with both translational and internal Doppler modes; that is, the moon's Doppler comes from range motion and libration. Range motion is a sum of lunar orbital and earth rotation effects. Libration fading is a consequence of interference from signals arriving from different specular sites, similar to the behavior attributed to a distributed meteorological target, as the relative lunar subpoint wanders a few degrees. The moon ostensibly (approximately) has the same face toward the earth. At S-band, about 90% of the backscatter arrives as quasi-specular components from the center of the lunar face. The optical moon subtends an included angle approximately the same as the sun, but the radio moon is smaller. The measured radar cross section, integrated over the lunar disk, is about 6% of the geometric cross section. With lunar diameter of 3460 km, the geometric cross section is large, but the free space path loss is large at a nominal 380,000 km range. Given the predictable pointing angle and range, of the moon, long integration times (even minutes) are possible. The Mile High Radar confirmed that 10 dB of post-detection signal to noise ratio can be obtained with a NEXRAD radar. Figure 8 illustrates approximately 40 lunar echo power measurements acquired over a 6 month period; with standard error about a least squares fit less than 1 dB. The lunar echo power measurement using long dwells with non-coherent averaging yielded range dependence steeper than R^{-4} in this test.

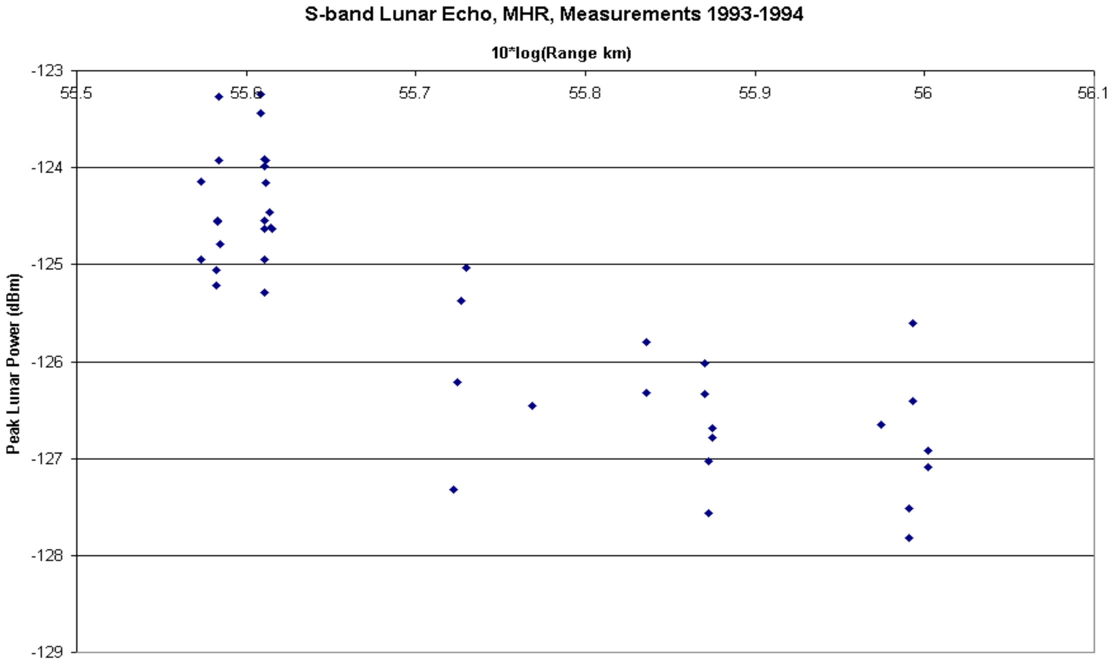

Figure 8 – Logarithmic Plot of Peak Lunar S-band Received Power Plotted against Lunar Range.

To recap, the moon's range and position can be predicted to the necessary precision for weather radar calibration. As a reflector its characteristics, such as Doppler and slow fading, need to be evaluated. However it is likely a wideband reflector over a microwave bands. The moon as a transfer standard has great strengths. Major drawbacks are two (1) its low SNR, which might be overcome by developing an algorithm for long integration times; and (2) lack of community understanding as a calibration aid. The sensitivity and power aperture of early weather radars were insufficient to use this target. The moon represents the least expensive two-way target and it can be accessed from all network locations.

3.1.5. Transponder Methods

Transponders, or active radar calibrators (ARC), are a type of engineering calibration aid, sometimes embodying a moving target simulator (MTS), consist of an antenna and a means, either mechanically or electrically, to modulate or make the echo unique. The transponder is a transmitter-receiver facility the function of which is to transmit signals automatically when the proper interrogation is received (FCC 2004). Transponders are commonly used in air traffic control for radar performance checks. Transponders are usually located at low elevation angles within the clutter regime and near the radio horizon. The devices may be left in place, or moved from site to site to accomplish calibration checks, and the transponders in concept are capable of "intelligent" power and phase compensation in the multipath propagation regime. Furthermore, several clever inexpensive "passive" transponders have been suggested, ones with frequency shifting and timing delay. Transponder design and placement requires avoiding range bin straddling loss, background errors and multipath contamination. Several devices located at different azimuths and ranges can help reduce these uncertainties and losses.

Drury and Frankovich (1992) describe the use of a tower-mounted moving target simulator transponder (FA-10360) for the Terminal Doppler Weather Radar (TDWR) shown in Figure 9.

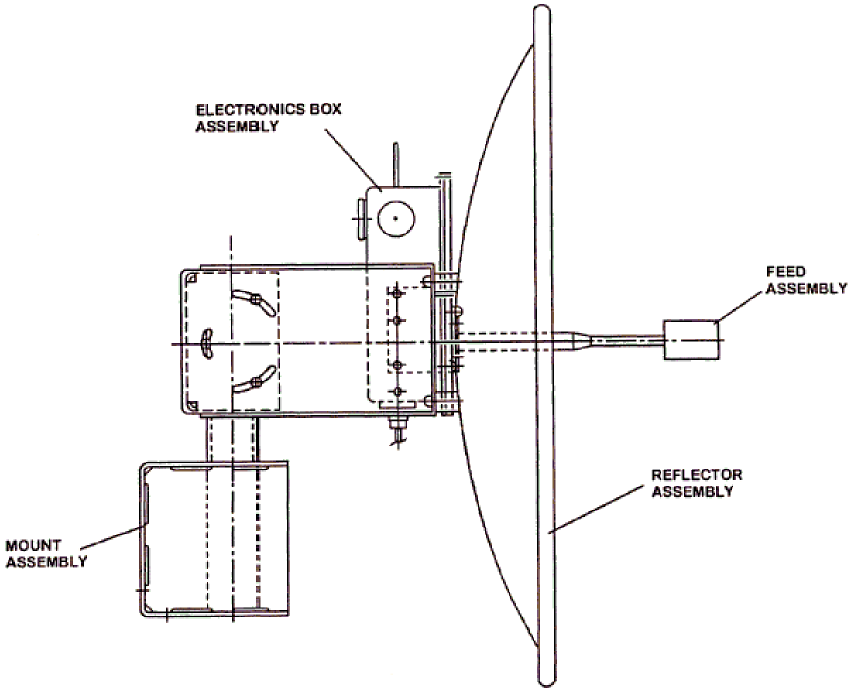

Figure 9 - Tower Mounted Moving Target Simulator (FAA 2000)

Brunfeldt and Ulaby (1982) identify a simple, amplified ARC with patch antennas used for airborne imaging radars and microwave remote sensing. Cohn (1978) describes the invention of an active, expendable radar repeater. Mawhinney (1987) describes the invention of a radar calibrator using a piezo-electric transducer to modulate the carrier. Meneghini (2001) and Kozu (1994) mention an ARC for the TRMM precipitation radar. By shifting the return in frequency or time the response may be separated from the skin return of the platform. Chisolm (1963) invented a simple modulated reflector with a calibrated offset frequency return. Bruder (1990) invented a constant-amplitude Doppler-producing radar reflector. Sarabandi et al (1992) and Freeman et al (1990) describe use of various targets including a polarimetric active radar calibrator (PARC). Rinehart (2001) presented calibration results from a nodding dihedral reflector at RADCAL 2001, the nodding action provided by an offset cam motor. The modulation of RCS provided the means for separating the dihedral echo return from the background. The dihedral was mounted on a tall wooden pole behind an intervening hill to minimize competing clutter return at the same range. However, when the line of sight path grazing angle is near zero, fixed losses from minimum clearance are speculative.

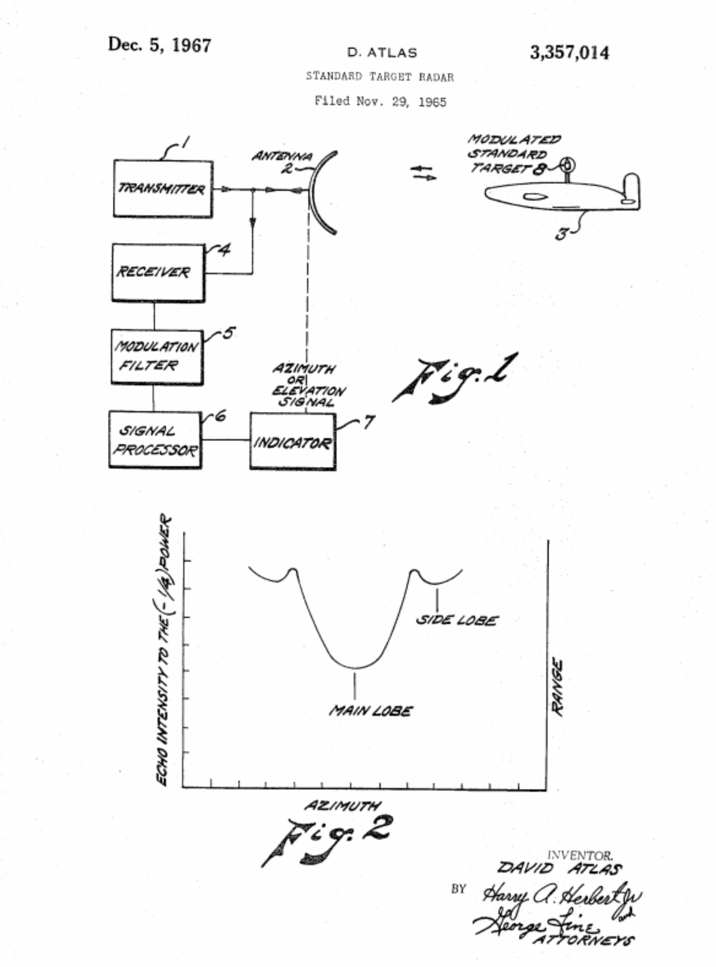

Figure 10 - Mechanical Modulation of External airborne Target (Atlas 1965). This is an example of a patent survey result.

In addition to use as ground-range calibrators, transponders can be airborne. In Figure 10 Atlas (1965) illustrates a curious invention that amplitude modulates the echo at a rotational frequency by means of a widebeam, spherical Luneberg lens, with an end cap, spun on its axis, thus providing a synchronous echo variation from a target of known cross section. The concept is intended to separate skin return by amplitude modulation of the calibration target.

3.1.6. Elevated Ground-range Methods

In this section we will attempt to unify several issues concerning calibration aids when mounted in the antenna far-field at practical elevations on poles and towers. Gain measurements of fixed-base radar antennas with large antennas has been difficult (near-field antenna methods described in another section may be an alternate) For calibration devices mounted near the ground, at low antenna elevation angles, there will be undesirable background caused by reflections from the earth's surface, vegetation, and structures, including the support towers themselves. The performance of calibration devices, whether active or passive calibrators, such as nodding reflectors, frequency-shift reflectors, transponders, moving target simulators, or tower targets of others, are adversely affected by the presence of the ground surface. Path clearance issues and near-earth reflection geometry generally produce a path loss with greater than 2 dB uncertainty. Furthermore, the reflection coefficient, reflection phase, and location of each dominant reflection surface are unknown and difficult to extract. Repjar et al (1982) described a distance extrapolation method, based on Newell et al (1973) that corrects for ground reflections in absolute antenna gain measurements. Their method requires a long, open antenna range with a sliding terminal, or sled-mounted tower, to vary the inter-antenna distance through the multipath regime. Jull and Deloli (1964) report a novel scheme in which they controlled the multipath by redirecting it using an artificial reflector surface in the near field of the remote terminal. Specialized techniques require a controlled radar range.

Elevating the far-field calibration terminal could provide some relief from multipath due to the narrow beam of the WSR-88D antenna. If the radar (1) is situated so that an elevated terminal is available, and (2) an angular area free of reflecting objects, and (3) the ground reflections are largely inhibited by surface extinction and antenna-pattern isolation, the radar location is likely one terminal of an excellent antenna range. Evaluation of such site attributes is made on a case-by-case basis (Evans 1990). One needs to know how high to raise the far-field terminals, and how far from the radar to place it. Real estate acquisition or leases may be required. There are radar sites where it may be difficult to find or construct a sufficiently elevated far-field terminal at a clear azimuth. Such is the design of ground-based antenna ranges, and they must be protected from construction along the radio frequency path. The antenna far-field, where the emitted wave becomes mostly planar is expressed as a function of antenna diameter D and wavelength

$$R_{farfield} = 2\frac{D^2}{\lambda} .$$

For perspective, Hacker and Schrank (1982) showed that gain error is approximately 0.05dB at R_{farfield} and 0.15dB at $R_{\text{farfield}}/2$.

Tower reflection. Tower targets have been employed for decades to coarsely check the radar power channels and pointing consistency. Clarke (2001) quantified the stability of tower echo from a C-band radar near London. Reflectivity variations are shown in Figure 11 from radar measurements of a free standing microwave tower located at 2.3 km range and 1.6 degrees elevation angle from the radar. The object of For Clarke's article is to discuss the utility of towers of opportunity as a radar calibration aid. The terrain profile described in the article seems good for minimizing reflections, with the terminal on a separate hill from the radar's hill. After selecting the "near-peaks" using histogram processing (a quality control step), the standard deviation of tower reflectivity was 0.26 dB during the highest-variance period of observation. For many large towers the scattering mechanisms and propagation are moderately stable and thus desirable. In fact, phase variations from clutter reflections have been used to measure boundary layer refractivity along the proposed path (Fabry 2004). As refractive index along the path changes, the power density and relative phase reaching the tower changes. For reference, note that Fabry estimated that a change of refractive index of 1 ppm, caused by a change of 1 degree C or 0.2 g/m^3 moisture, or a rainfall rate of 13 mm/hr, alters the composite path length by merely 200 degrees at 30 km round trip at S-band.

In Figure 11, Clarke ascribes the large dips in tower reflectivity at C-band to a wet radome. In practice, modern radars like the WSR-88D exhibit significant intrinsic system gain stability. With path repeatability, monitoring the return from clutter targets such as these could build confidence in short-term system stability in dry radome conditions. However repeatable at a single site, the return from an unknown target will likely improve intra-site reproducibility. Furthermore, if a tower fixture is added or removed, the composite RCS of that tower may change noticeably, and thus process monitoring, quality control, and tower inventory methods are important.

For WSR-88D calibration there are three important points to note from Clarke (2001). First, "near-peak" echo was numerically separated from environmental effects (loosely, background) by editing redundant data. For a calibration target in an uncontrolled environment, process monitoring and data quality control methods were employed. Second, the signal from an unqualified target, or a target that is not independently traceable, will likely not add much to improve reproducibility among sites. Third, wet radome losses must be treated if variable system losses are to be limited to less than 1 dB.

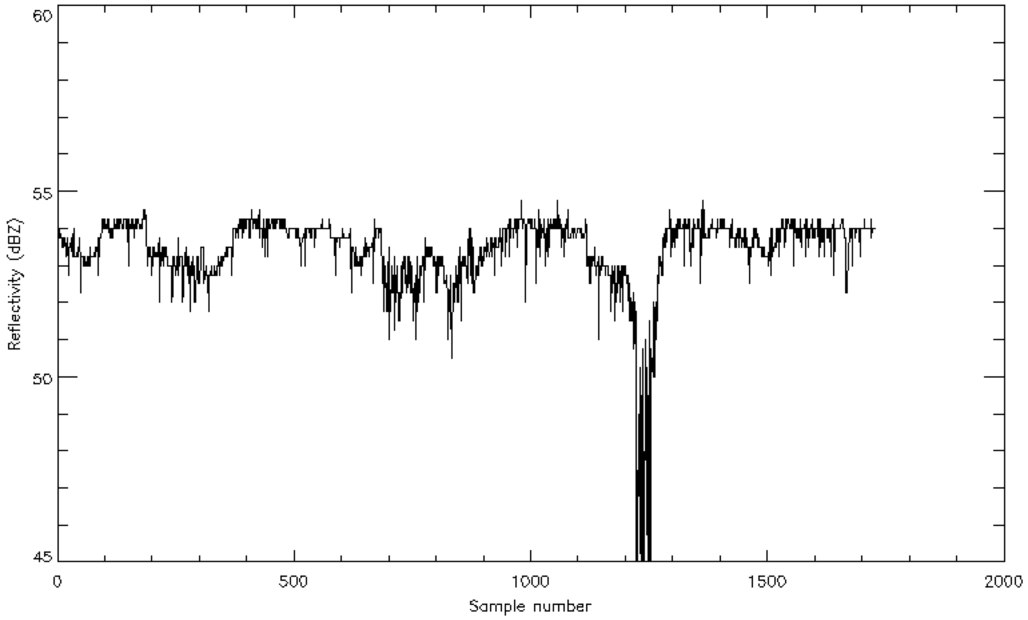

Figure 11 - Reflectivity Measurements from a Microwave tower at 5-minute intervals for 6-days (Clarke 2001).

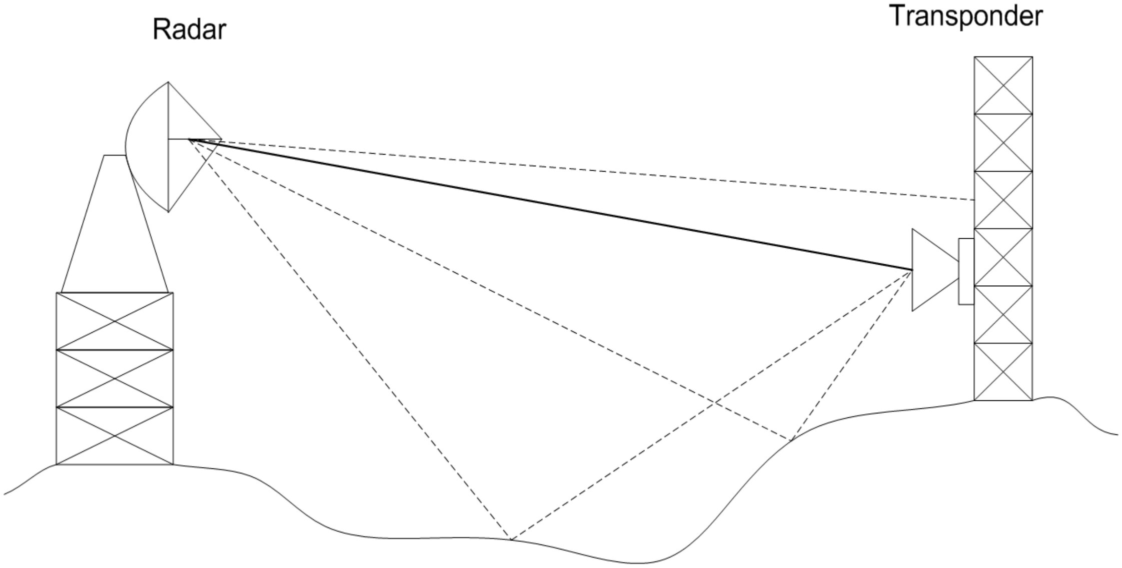

Figure 12 - Layout of Elevated Ground Range with Far-Field Terminal

Elevated ground ranges. Figure 12 is a schematic elevated ground range for passive or active terminals showing multipath, reflected rays that interfere with the main, direct propagation path. At the terminal location we mount a calibrated antenna, calibrated RF source, and a calibrated receiver. The terminal could be equipped with a standard test suite (a gain horn, a continuous-wave source, and a power meter) or it may be a bent-pipe or regenerative transponder. Because of the low-angle path, landform and clutter reflections need compensation if a calibration is to be better than 1 dB. The characterization of the path's transfer function, called "channel sounding", is accomplished by directly measuring the complex transfer function of a given fixed path as a function of time and/ or frequency.

For WSR-88D tower heights of 5 to 30 meters, the multipath differential delays are seldom longer than 3 nanoseconds. The literature is sparse on using channel equalization methods to remove the effect of multipath on an outdoor elevated ground measurement range. Consequently, on 31 August 2004 a confirmatory experiment was conducted at the CSU-CHILL radar to attempt to measure the RF channel's response over a ground-based path and time-of-arrival of multipath events. The CSU-CHILL staff has two standard far-field locations for calibration terminals. The most reproducible of these is to the southeast of the radar over level terrain at a distance of 1.6 km. The source, consisting of a standard gain horn and a signal generator, was varied in height using a rented 30-foot lift. The standard gain horn had a beam width of approximately 45 degrees. Path loss was measured as a function of lift height of 6, 13, and 26 feet AGL. In the absence of vehicle traffic the path was stable and repeatable. The lift's height variation of the source horn historically contributed somewhat more than 1 dB of mean amplitude variation. Passing trucks and aircraft modified the path loss on an instantaneous basis by 10 dB or more by multipath additions, though the vehicles were not in the line of sight. Figure 13 shows the elevated ground-range view from the source toward northwest. The CSU-CHILL is in the distance across an open flat, ground measurement range with elevated terminals.

Figure 13 - View northwest from the source terminal at 26 feet AGL toward the CSU-CHILL radar.

Channel sounding was attempted with two waveforms. For waveform test, the excitation signal was 20MHz QPSK from an Agilent E4482C Vector Signal Generator. The receiver was an S-band low noise amplifier ahead of an Agilent 89640A Vector Signal Analyzer (VSA). The data stream from the source was pseudo-noise sequence (PN) recovered and correlated at the VSA receiver. Both source and receiver exhibit exceptionally low phase noise. Received power and delay distortion was measured with the VSA, by means of an adaptive equalizer of 36MHz bandwidth. In Figure 14, the path loss measured using the VSA receiver is plotted for three heights (large squares), together with path loss predicted from 2-ray models and the calculated free space path loss of –105 dB. Integrated delay distortion up to several hundred nanoseconds was measured at approximately 40 dB down relative to the average received power. This figure records the CSU-CHILL 1.6 km channel sounding test data and includes predicted two-ray path losses: (1) with wide-beam source and receiver horns, and (2) with a wide-beam source but narrow-beam receive antenna providing significant reflected ray isolation. Actual path loss was measured as the source horn was lifted from 6 feet to 13 feet to 26 feet AGL to create variable reflection delays.

For the second waveform test, the Agilent E4482C was programmed to excite the horn with a 4-microsecond square burst at a 1 kHz repetition rate. The waveform was sampled with an Agilent 54855A digital oscilloscope with a 6-GHz bandwidth. Visual examination of the received spectrum envelope showed no temporal distortion whatsoever. Additionally, there was negligible delayed ray energy was seen on either the leading or trailing edge of the RF burst, suggesting that distortion from static, differential path delays of a nanosecond.

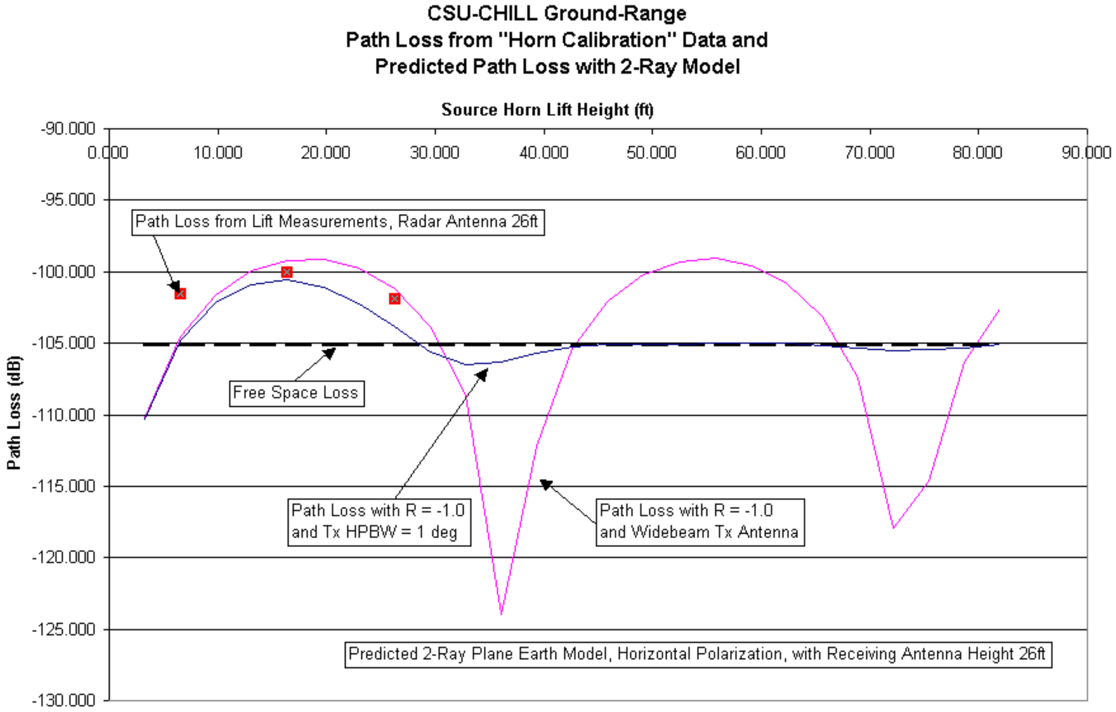

Figure 14 – CSU-CHILL 1.6 km elevated ground-range channel sounding predictions, and test data as transmit horn was raised through the height of CSU-CHILL antenna center (8 m or 26 ft).

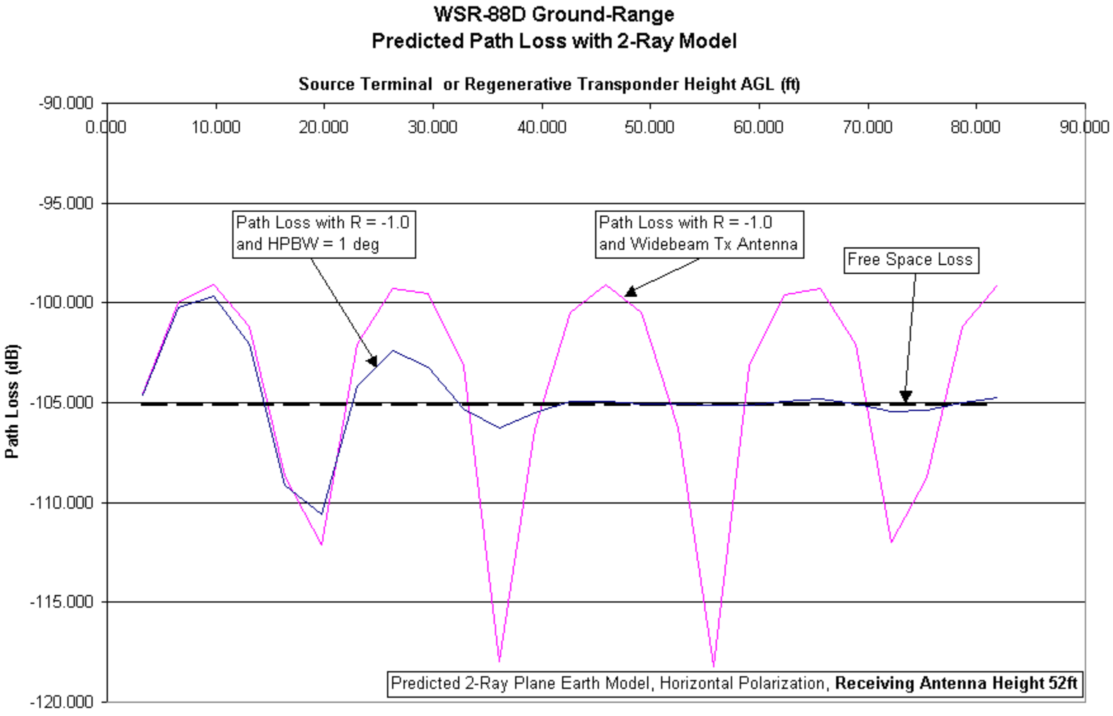

Figure 15 – Two-Ray Prediction of Path Loss for WSR-88D Elevated Ground-range Calibration with radar receiver at 15 m height.

Figure 15 shows predicted one-way path loss over flat earth from the 2-ray propagation model having the source horn at 15 m. The receiver height was varied from 0 to 80 ft (x-axis) for 2 cases: 1) using wide beam receive antenna, and 2) using 1-degree narrow beam transmit antenna.

Though natural terrain is rough, at very low grazing angles "reflection" from natural terrain is often specular. Terrain roughness causes more path loss as the grazing angle increases. Scattering loss from a rough Gaussian surface at low grazing angles is often approximated as

$$L = \exp\left[\left(\frac{-4\pi H_{rms}\sin(g)}{\lambda}\right)^{2}\right]$$

where H_{rms} is the root mean square surface height variations (roughness), g is the grazing angle between the ray and the surface in radians and λ is the wavelength. Figure 16 depicts the scattering loss from rough terrain between an S-band radar and a calibration terminal for three grazing angles. Loss increases noticeably with angle and when the roughness exceeds one wavelength. Most clear, flat, ground-based, calibration paths have grazing angles to the terrain of approximately 1-degree and differences between the r eflected and direct paths of less than 1 meter or less than 3 nanoseconds. To obtain the transfer function of a microwave channel in real time would require a signal bandwidth of well over 1 GHz, which is difficult with the present equipment.

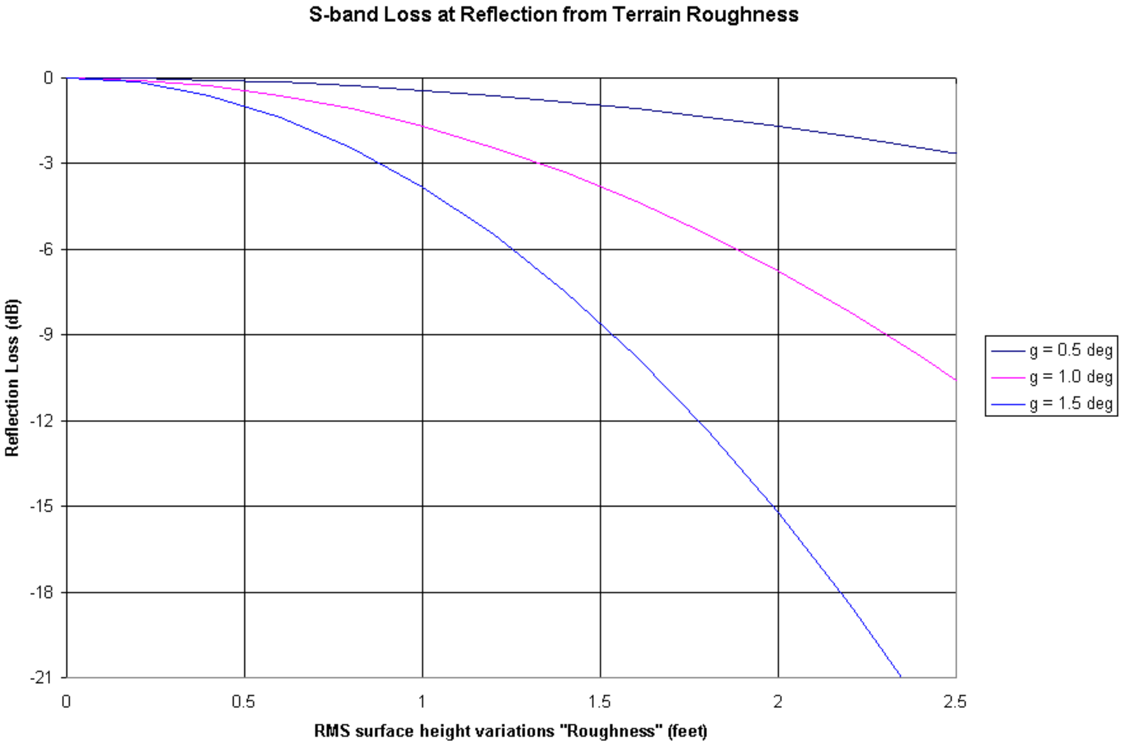

Figure 16 – Predicted Loss from Terrain Scatter Between S-band Radar and Calibration Terminal

Ultra-WideBand waveform techniques. In concept, multipath channel sounding using ultra-wideband (UWB) waveforms has the capability of resolving the direct from the reflected path energy at sub-nanosecond delays. Kissick (2002) describes UWB signal characteristics, Brunson et al (2001) describes UWB impact for federal radio systems, Agilent (2000) describes other UWB applications and Andrews (2000) discusses UWB time domain reflectometry methods. More specifically for our purposes, Muqaibel, et al (2001) describes UWB channel measurement methods. Real-time methods have been proposed to delineate reflected from direct echoes, such as the invention of Alon (2002), but these depend on a large path difference relative to the resolution cell.

The FCC permits short-range outdoor UWB communications and radar devices regulated with other Part 15 permitted devices (FCC 2004). Subpart 15.521(d) restricts the transmit power to –41.3 dBm/MHz under the permitted conditions, which is sufficient power for short two-way radar paths. Presently available bands are 3.1 to 10.6 GHz and 24 to 29 GHz. In addition to this allocated UWB bandwidth, we note that test equipment and wideband antennas are available. This is an area for fruitful evaluation if stable far field external calibration at a low height is desired.

It may be possible to measure the individual returns and resolve the channel impulse response by ultra-wideband methods Kim (2004), however these approaches exceed the intrinsic bandwidth of the WSR-88D and appear to require considerable future investigation. It may also be possible to transmit several measured CW tones across a significant frequency band and solve for the separate returns by measuring their differential power, but this idea, like the UWB schemes, is likely to exceed the bandwidth of the WSR-88D antenna (a few hundred MHz).

Most locations will have path geometry more complicated than the CSU-CHILL path and may not be well behaved temporally. A complex scattering model may be required to diagnose the interference fringes at each orthogonal polarization. Moeller (1966) discusses error sources for main beam gain, tracking error, polarization angle error, and ellipticity error and provides worst-case formulas for elevated ground ranges in uneven terrain. Also he describes the standard radio path procedures for determining reflection points from a surveyed terrain profile. Dominant reflections may also occur from vertically aligned structures in built-up areas and moving vehicles. The general rule is not to illuminate the ground or other structure with any part of the main radar beam. In our survey, we subsequently discovered that Beck (2004) was awarded a patent on a channel sounding method as applied to antenna testing on an elevated ground range.

3.1.7. Near-Field Measurements

A major limitation in measuring the far-field pattern of a large antenna is overcoming the far-field separation distance problem which exceeds 1 km for the WSR-88D. Measurements carried out in the antenna's proximity are termed "near-field" measurements. Techniques developed in 1970 at the Technical University of Denmark transformed near-field measurements into far field antenna patterns numerically. NIST now uses near-field antenna measurements as the standard for high accuracy antenna measurements. A planar-scanned commercial product was marketed in 1984 by MI-Technology (formally Scientific-Atlanta). Spherical-scanned near-field analysis techniques have been further commercialized during the last decade yielding affordable antenna measurements for a wider variety of geometries. Figure 17 shows an example of an outdoor, near field antenna pattern measurement range, depicting a scanner and a vehicle-mounted antenna under test (AUT) on the turntable.

Figure 17 – Example of a Spherical Near-field Antenna Test Facility (The Howland Company).

Far field co-polar and cross-polar patterns can be computed at any distance from the antenna from near-field measurements. Phase measured relative to a well-defined point allows determination of the antenna's phase center. Arbitrary cuts can be contoured. The coordinate system can be defined relative to the antenna's flange or some other mechanical reference on the antenna. Axial ratio, tilt angle and polarization of the electromagnetic field can be determined for specified directions. A dual-polarized probe can measure the two polarization components simultaneously so that errors due to gain drift between the two measurements are eliminated. Correction for the polarization of the probe itself is applied to increase the final accuracy.

When a full sphere of near-field data has been measured, the ratio between peak and total radiated power can be calculated. This peak directivity is accurately determined because both the peak level and the power are rigorously calculated from a large number of near-field values. Wittmann and Stubenrauch (1990) discuss the effect of probe antenna corrections and compare measured spherical near-field against measured planar near-field results.

The time needed for spherical near-field testing of a given antenna depends upon a number of factors. Mechanical alignments between the probe and the AUT may take several hours, but elapsed time is minimized through fully automatic near field data acquisition. The acquisition time required for a complete spherical near-field scan of the AUT increases with the antenna diameter in wavelengths. Measurements outside the main lobe and first few sidelobes can be omitted resulting in a short turnaround time by accepting a small degradation in the accuracy of the results relative to scanning all spillover- and back-lobes.

3.1.8. Reflectivity Comparison Methods

An important class of meteorological calibration aids is represented by selected precipitation targets of sufficient signal-to-noise ratio. These targets permit quantitative comparison when the distributed target is in an optimum observing geometry of each weather radar. Though these common volumes have unknown radar cross-sections, the radars are operating on the targets for which they were designed. When radar systems have the same radio frequency band, antenna, and processing characteristics; and when the target consists of broad drop distributions that exhibit low wavelength selectivity, usable comparisons can be made. Boustany (1999) describes a sliding-window reflectivity comparison technique. Gourley (2004) suggests that the dominant sources of variation when comparing neighboring WSR-88Ds are (1) different beam propagation paths from variable thermodynamic profiles, and (2) beam height differences of up to 750 meters. Sometimes reflectivity histograms are employed to compare shape and mean of distributions.. Figure 18 shows an example of Gourley's meteorological calibration aid that analyzed differences between the Oklahoma City WSR-88D (KTLX) and adjoining radars over a seven-month period.

The fluctuation level is dependent on commonality of volume filling, type and size of scatterers, processing and filter compensation. The difficulty of the comparison increases with slant range because of the meteorological factors, particularly beyond 120 km. There are practical difficulties in automating this comparison method because target suitability is always an issue.

Gourley (2004) comments that after 10 days of averaging, the mean reflectivity differences converge on the long-term difference mean. Trends of the long-term mean difference may be related to the relative calibration difference of the radars. The largest long-term differences found in this analysis method are around 3 dB.

A plausible suggestion for a meteorological calibration aid is a small, mobile instrumentation radar, a de facto "traveling standard radar", for comparison with WSR-88Ds though mutual observation of precipitation. Examples of weather radars on wheels have been seen in many recent research projects. A specific example is a set of low power, vertically- or fixed-pointing radars dispersed to WSR-88D sites for extended comparisons. Direct comparison using nearby meteorological targets is an advantage. Calibration, maintenance, progress monitoring, and elapsed time are issues to be considered. At certain locations it may be weeks for optimum precipitation targets to materialize. A small radar may require shorter wavelength (comparison made across wavelength differences require a distributed target model) or large beam width (require that comparison be made on uniform targets).

Though "meteorological calibrations" via precipitation reflectivity comparisons can effectively monitor relative performance, the methods are not traceable, and in a calibration sense are complicated by variations of the meteorology and measurement process. A deficiency of such aids is that a detailed engineering diagnosis of calibration state is unlikely from the relative information provided. Technicians in the field require repeatable, specific, on-call procedures to identify, and against which to adjust, instrument subsystems.

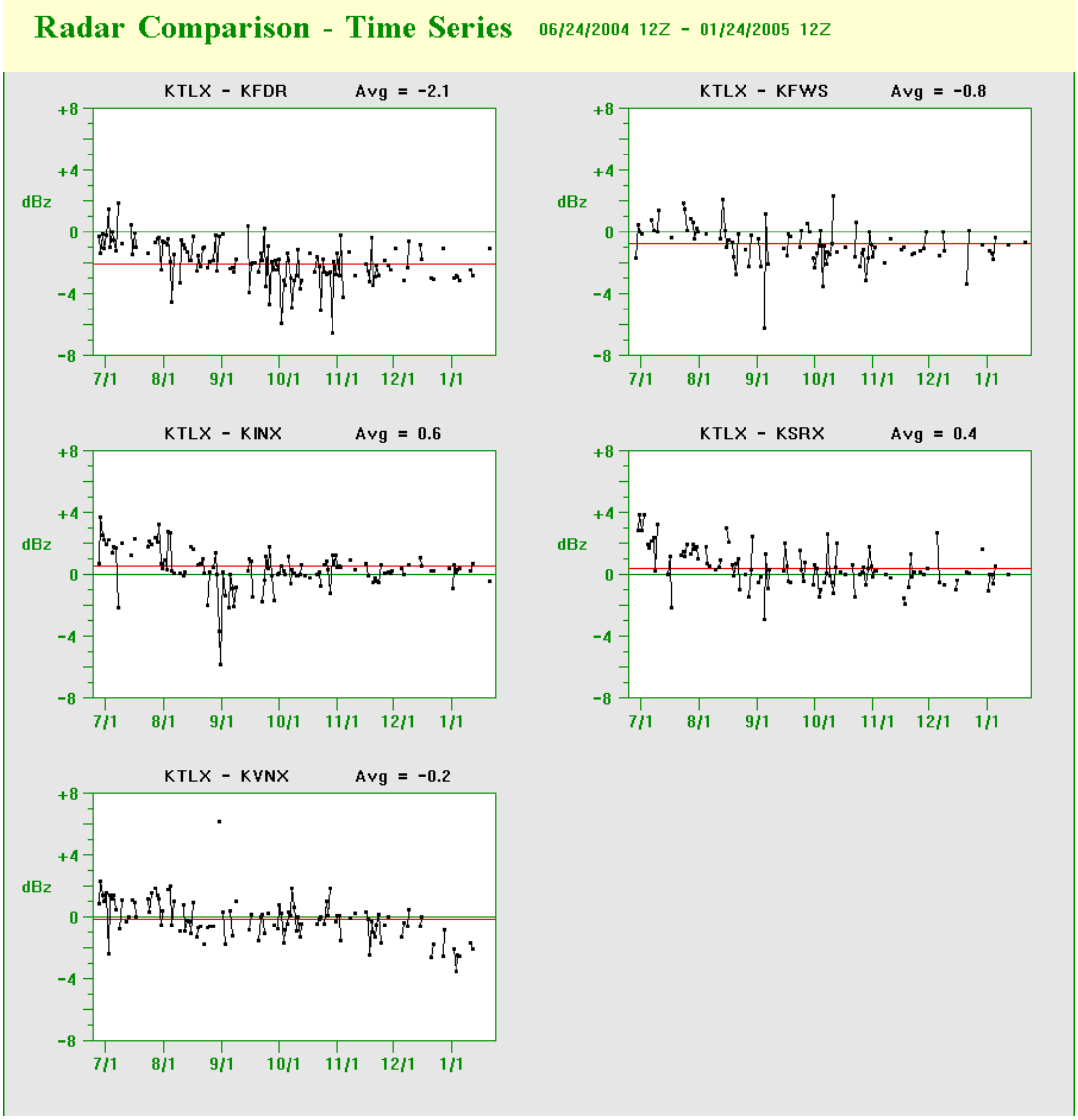

Figure 18 – Precipitation Reflectivity Differences Among Adjoining Radars surrounding KTLX

3.1.9. Rain gauge Comparison Methods

Many articles have described the effort of radars reflectivity with precipitation gauges and distrometers, another valuable type of meteorological calibration aid. Radar reflectivity “adjustment” is an alternate term for “calibration”. The WSR-88D precipitation processing subsystem includes a gauge adjustment to compensate for blockage and calibration bias errors, and is clearly required for any hydrometeorological program. Atlas (2002) describes use of vertically-pointing radars and distrometers to develop fundamental equipment (instrument) calibration. Ulbrich and Lee (1999) used drop size distributions the check WSR-88D calibration in South Carolina. Zawadzki (2001) summarized the results for RADCAL2001 from a distrometer and profiler (near-vertically-pointing) radar error analysis relative to Z-R formulas.

As a calibration aid the “raingauge comparison” methods run the requirement for precipitation at the location of interest, and are more suitable as an end-user evaluation than in the practice of instrument calibration. Control of variation arising from climate, storm structure, and gauge instrumentation considerations is difficult. Much has been and will continue to be published on this topic, for example, Austin (1987), Joss and Waldvogel (1990), Smith et al (1990), Fabry et al (1992), Ahnert et al (1983), Rasmussen et al (1989), and NOAA (1991), and Wilson and Brandes (1970).

3.1.10. Dual Polarization Consistency Methods

A number of investigators have suggested rainfall estimation techniques using the differential measurements of a dual polarization weather radar. Dual polarization methods use amplitude and phase differences between the horizontal and vertical pulses propagating through the precipitation medium (Sachidananda and Zrnic 1987) to calculate a rain rate. This important aspect of microwave remote sensing of precipitation is presently being developed and is planned for the WSR-88D implementation in the next few years (Doviak and Zrnic 1998). While an ultimately useful “meteorological calibration” comparison method, it is not presently available and may prove of comparative value only in heavy rainfall. Vivekanandan et al (2001, 2003), Hubbert (2003), and Giangrande, et al (2004) describe methods that employ differential power measurements and propagation phase differences to support the two-channel calibration problem. Hubbert’s (2003) proposal requires separable cross polar measurements to be implemented in the instrument design. Giagrande (2004) discusses consistency algorithms. Clearly this category of approach provides important data sets for calibration process monitoring.

Differential polarization variables will likely not diminish the resolve to reduce horizontally polarized reflectivity measurement uncertainty (Sirmans 2004). Furthermore, the current WSR-88D pedestal limit of 60 degrees elevation angle precludes viewing rainfall from directly below where the cross section of the drops is more circular and allows a differential reflectivity calibration check, as frequently employed on research radars. The WSR-88D network needs an external calibration aid system to verify performance of the dual polarization modifications.

3.2. Procedures: Evaluation criteria

In the effort to discriminate the potential utility and rank the different proposed WSR-88D calibration aids, we used the following sets of considerations. These are the “filter” questions that we used. Development of an idea leads to further issues and questions.

Categories of “point” sources:

Reflecting calibration targets (spheres, trihedrals)
Active calibration emitters/receivers (transponders)
Radiometric emitters (noise)

Categories of “radar measurement range” geometries:

Celestial techniques (solar-, lunar-, stellar-flux transfer)
Ground-range reflectors/transponders (tower-mounted)
Orbiting reflectors/transponders (near earth, lunar)
Airborne reflectors/transponders (helicopter)
Tethered reflectors/transponders (balloon)
Near-field emitters/reflectors (at radome surface)

System integration:

What are the engineering dependencies of the proposed external technique, such as processing, communications, and change proposals?
Will it support the design and implementation system upgrades, such as pulse coding, dual polarization sensing, and fast scanning?
What is the level of required development in hardware, software, interfacing, and installation?

Error control and uncertainty:

What is independent of the calibration traceability of the radar system itself?
Can the idea, if implemented, accurately measure target range?
Will it measure end-to-end beam angle readout error?
Is it amenable to statistical process control methods?
How are its calibration reference ports translated?
Will it achieve a two-way "end-to-end" measurement (inclusion of transmit as well as receive)?
What is the budgeted experimental standard deviation that the idea embodies from each subsystem, antenna/radom, receiver/processor, and transmitter?

Resources:

Are developers of this idea available with expertise, shop, and test facilities?
What is the idea's potential ease of use, portability, and cost in dollars and staff resource?
What could be its degree of automation, ultimately governing a certain frequency and economy of use?
What level of staff training required?
How much operational outage will it entail?
Is real estate needed, permanent or temporary?
Will it be acceptable to the technical committees and to the user community?
Could it be compatible with other radars, such as the FAA's TDWR?

4. Proposed External Calibration Aids

The following eight external calibration ideas were selected from the surveyed material using the questions and issues above. The selection criteria and scoring matrix are given:

(1) An external test set method
(2) A drifting calibration sphere method
(3) A near-field antenna pattern method
(4) Calibration process monitoring software
(5) Enhancing the offline solar flux method
(6) A high-tower transponder method
(7) Airborne/orbiting transponder methods
(8) A lunar reflection method

4.1. External Test Set

The basic WSR-88D engineering calibration can be verified with a portable independent test equipment package. Sirmans (1992) describes the manual version of the idea. With the appropriate supporting software and hardware, Sirman's data collection and calculation procedures can be automated employing a test set. The basic radar engineering calibration has never been verified at many sites. A judicious selection of measurement points and signal injection points could yield a fully independent, electronic calibration. Radar downtime would be required, but it would be designed to be minimal. Solar flux transfer measurements for estimating system gain are also possible using the antenna and pedestal if a receiver interface is installed. The practice of this idea could be a test set that "hangs" on the pedestal of an operational WSR-88D and provides real-time peak transmit power measurement, delayed injected signal measurement, precise GPS timing, solar flux antenna measurement. It could be shipped to a WSR-88D radar site, installed, and operated normally until weather conditions allowed for calibration trials.

The principal test set interface is with the RF portion of the WSR-88D. If designed with the waveguide upgrades for dual polarization, translation of references can be eliminated or minimized. Software would be needed on the WSR-88D to point and scan the antenna, to set the signal processor mode(s), and to acquire a subset of the base data for offline analysis. Commercial test equipment has increased its accuracy, stability, communications options, and performance-to-weight ratio over the last decade.

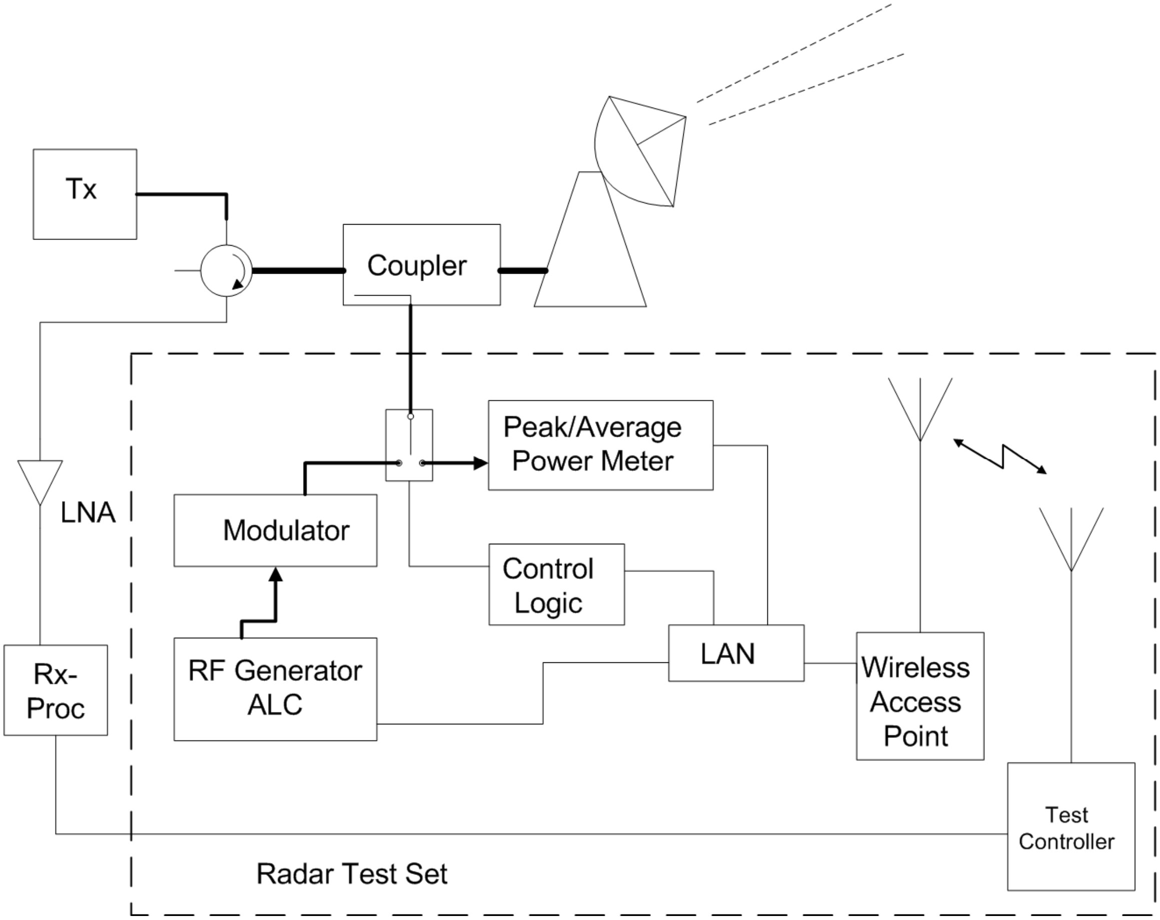

Figure 19 - Radar Calibration Transmit/Receive Test Set Concept

The test set illustrated in Figure 19 could be designed with a low noise receiver for measuring the antenna gain via the solar flux transfer method and packaged for temporary placement on the elevation axis. Solar flux measurement paths are not shown. Depending on the complexity of the test set, it is possible to measure transmission line mismatch and receiver dynamic range. This package can externally and independently verify the existing engineering calibration and the existing Sun Check using the base data output from the WSR-88D processing, with the radar operating in weather data processing mode.

The WSR-88D's antenna gain formula should be verified by another calibration aid measurements at a significant number of sites across the radar band. Complete independence from the solar observatories could be realized by an auxiliary tracking antenna/receiver system to measure solar flux simultaneously with the flux through the WSR-88D antenna; however this approach makes the technique more complicated to implement. University physics departments have attempted absolute solar flux monitors, but are challenged to build a consistent measurement apparatus in a radio-interference-limited environment. Consider, however, that a separate low-noise portable receiver added to the test set might permit antenna gain measurements independent from the internal check.

The Department of Defense (DoD) is developing a specification for networked automated test systems called NxTest (Heftman 2004, Rozner 2005, also see Test and Diagnostics Consortium below in Appendix A). The devices will be local area network LXI (LAN Extensions for Instrumentation) compatible, smaller and lighter, virtual front panels, but with the functionality of front-panel instruments. The first commercial NxTest instruments were due in 2004. NxTest and LXI (Hughes, et al 2002) may offer implementation benefits to a WSR-88D test set.

To summarize, WSR-88D engineering calibration could be verified with a portable independent test equipment package. With the appropriate supporting software and a judicious selection of designed-in signal points, a fully independent electronic calibration aid could be implemented. Independent antenna gain measurements are possible using solar flux transfer methods. WSR-88D test software will be needed to set the processor configuration and log calibration data. The key point is to verify the system's engineering calibration by independent, semi-automated means.

4.2. Drifting-sphere

Metallic spheres find broad acceptance as engineering calibration targets for their true end-to-end calibration and immediate traceability. Atlas and Mossop (1960) reported a dynamic method by which a relatively large metallic sphere was carried aloft by a balloon and tracked with a theodolite while drifting downrange as depicted in Figure 20. As previously discussed, conducting spheres have a distinct advantage in that they are a fundamental standard. With its 3-axis symmetry, its RCS is aspect independent and it does not produce any cross-polarized backscatter. As a first approximation, the RCS of perfectly conducting spheres whose circumference (πD) are 10 or more wavelengths have an RCS nearly equal to the geometric cross-section. Atlas (2002) concentrates on spheres in his perspective of radar reflectivity calibrations. He further describes several attempts at radar calibration with spheres, including spheres towed from a helicopter, metalized table tennis balls dropped from a light aircraft, a metalized balloon released from aircraft, pellets shot from a pistol, and a tethered balloon with a sphere.

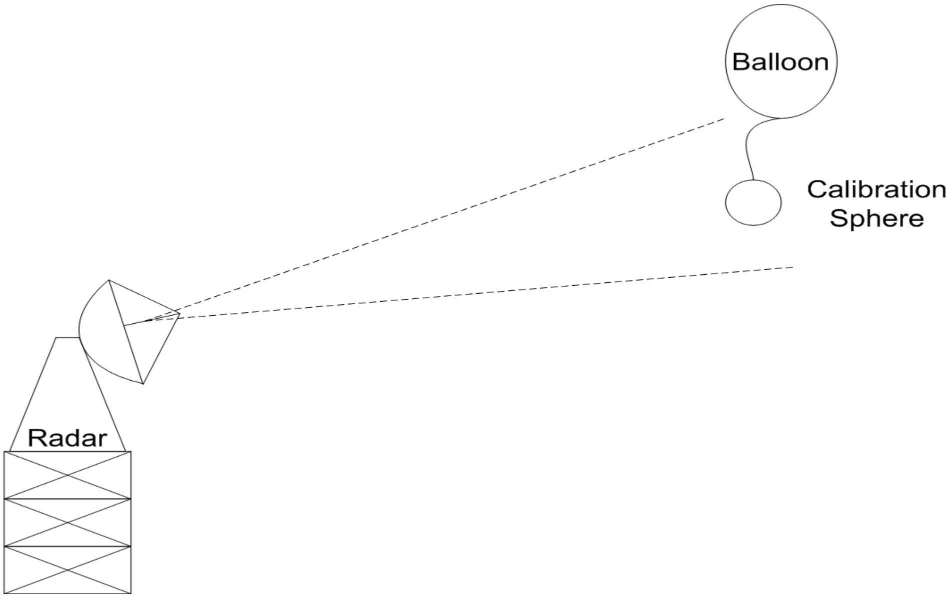

Figure 20 - Schematic for Dynamic, Drifting-sphere Calibration

Background mitigation is extremely important. If the metallic sphere is chosen large enough, the RCS of the dielectric materials of the latex balloon and tether line will be several orders of magnitude lower than the sphere.. When using small spheres as radar calibration standards at low altitudes on otherwise clear days, caution should be observed to insure that bird or insect return does not bias the sphere echo and erratic movements does not incorrectly influence tracking. These complications may be seen especially during the first minutes of flight when the balloon is within the boundary layer. Mueller (2004) related that he once observed through a tracking theodolite two birds circling the balloon-born sphere. Unusual situations will accompany any calibration method conducted in the field as opposed to an anechoic chamber. Process control and data editing are required because no single measurement is sufficient to establish a calibration.

Because the free-floating sphere will generally drift away from the radar site, a check of the instrument's range response is possible, knowing the sphere's location. Furthermore, since ranges up to 100 km are encountered, it may also be possible to evaluate two-way atmospheric absorption loss along the track. A drifting sphere will check the receiver system over a large dynamic range of the received power.

There are three caveats for calibrating with non-stationary sphere targets:

1. Maximize the time on target through efficient tracking. This reduces scanning, backlash, and straddling losses.
2. By efficient design and implementation, maximize the sphere echo relative to background, interference, and noise.
3. Perform a thorough data analysis. This usually means employing as much of the tracking data as possible in an analysis model.

An uncertainty budget in Table 2 for the drifting-sphere method follows the template of Wittmann et al (1994). The analysis assumes that the backscatter from a perfectly conducting sphere is independent of aspect angle and the sphere as a radar target does not scintillate. Dominant error components are "Average Illumination" (beam scanning losses: beam shape losses, & backlash losses) "Nonlinearity" (range straddling losses), and "Noise Background" (low desired signal). The dominant error components produce lower rather than higher displayed RCS, especially scanning and range straddling losses. The Average Illumination component can be controlled by processing of the echo signal.

	Component of Uncertainty	Standard Uncertainty
1	Average Illumination	0.5 dB
2	Target-Background	0.10
3	Cross Polarization	0.05
4	Amplitude Drift	0.10
5	Frequency	0.01
6	Integration	0.05
7	Phase-Amplitude Imbalance	0.01
8	Near Field	0.10
9	Noise-Background	0.14
10	Nonlinearity	0.06
11	Range	0.02
12	Target Orientation	0.01
13	Calibration Target	0.10
	Combined Standard Uncertainty	0.56 dB

Table 2. Proposed RCS uncertainty analysis for dynamic, drifting sphere calibration target based on the procedures of Wittmann et al (1994) and Matyas and Kelsall (1991).

Computer control of tracking and processing can produce substantial improvements in consistency and ease of data acquisition. Less costly test execution can be expected from development of well-designed test software for the WSR-88D.

Sarabandi et al (1990) and Sarabandi and Ulaby (1990) discuss sphere calibrations for dual polarization radars. Accordingly, a sphere simplifies calculation of the unknown radar responses, the scattering matrix can be derived exactly and it is insensitive to target orientation. Bergada et al (2001) describe another procedure using an air gun to propel spheres vertically into the beam from below, reaching their zenith in the center of the beam. Only a small percentage of the shots were of sufficient centering to be useful.
Muth and Conn (2003) explain a processing method for improved RCS extraction.

4.2. Near-field Antenna Techniques

Near-field measurement methods were described earlier as a new variation for large antennas in the field, that can provide co-polar and cross-polar results. If amplitude and phase are measured on a known elevation, azimuth, range, and polarization grid near the antenna aperture and the surface need not be a plane as typically has been done in the past. This data set is then processed to yield a far-field-equivalent measurement set. Careful control of uncertainties in the near field data set produces an accurate far-field depiction. The WSR-88D, with its elevation-over-azimuth computer-controlled pedestal, and radome may make a suitable near-field measurement testbed. Injection of signals into the transmit waveguide and reception with a radome-mounted probe antenna could provide forward (radar-transmit-side) calibration of the antenna system and transmit plumbing at system reference points. Likewise, injecting the test signal at the probe antenna and receiving through the WSR-88D could yield reverse (radar-receive-side) calibration of antenna and receive plumbing to selected reference points. Azimuth cuts and elevation cuts through the far-field pattern may be calculated to the uncertainty delivered by near-field testbed geometry. Accumulation of small errors limits the accuracy of the technique, but this limitation may be simulated.

If the whole sphere of data is collected, “absolute accuracy” of the main beam gain might be 0.25 to 0.50 dB and the same for a -20 dB sidelobe level. There is no equation for these uncertainties, but rather a budget of approximately 10 to 15 main error contributions, most of which are either measured or estimated with computer simulation. Howland (2004) and Masters (2004) estimated that “reproducibility” on the WSR-88D could be made appreciably better than 0.5 dB if the reflector aperture could be completely scanned. However, if only two cuts of the near-field are acquired (a single azimuth rotation of the antenna followed by a single elevation rotation of the antenna), then additional uncertainties arise from the limited amplitude and phase depiction. These error levels assume symmetry of the antenna near-field. The best way to estimate a WSR-88D near-field uncertainty budget is with a limited set of actual measurements and iterative use of the processing program by an experienced near-field antenna engineer.

Near-field techniques could be introduced into a complete WSR-88D calibration method. As the WSR-88D is a phase coherent instrument with a high fidelity digitizer/signal processor, it may be possible to measure the transmit pulse itself with the probe horn, recording its amplitude and phase as a function of antenna position, to produce a near-field power density that can be transformed to a far-field pattern. Likewise, excitation of the receive aperture with a delayed version of the transmit pulse could produce a set of near field measurements capable of far-field transformation. Thus, transmit and receive calibration constants are checked to within near-field measurement uncertainty, radar timing stability, and the capability of the signal processor. Near-field techniques deserve consideration as a calibration aid for fixed-base radars such as the WSR-88D (S-band) and similar radars such as the TDWR (C-band).

4.3. Enhanced Radiative Flux Transfer (Solar Flux Transfer)

The radiative flux transfer techniques, most commonly solar, are in the category of passive radiometric engineering calibration techniques using two receiving terminals, the radar under test and the reference antenna, usually located at a solar or astronomy observatory.

There reasons to rely on the sun as a microwave source and a solar flux transfer (SFT) standard as a calibration aid. Though the sun is a highly variable microwave source, from experience it is “top dog” among external calibration sources. However there are shortcomings described below. The dominant benefit is that as a calibration check, it can be automated and if conducted properly is inexpensive for the benefit gained.

Pratte and Ferraro (1995) completed an exhaustive study of the Sun Check implementation on the WSR-88D and provide suggestions for improving the solar flux transfer technique as practiced in the WSR-88D network. The object of the study was to reduce the experimental variance of the technique and help monitor intra-network calibration data at an engineering level. Ancillary measurements can be made and recorded at the time of the solar flux measurement to help monitor and understand system performance.

The highly variable output of the sun in times of high sunspot numbers limits its utility as a noise source of known output relative to the solar patrol observatories because of the difficulty of separating radio bursts from quiet sun emissions,. The solar flux disseminated is not the actual measurement, but a derived quantity that estimates the underlying, slowly varying emission component. Many large antennas are calibrated using the very stable celestial source Cassiopeia A for which Guidice and Castelli (1971) claim is known to an absolute accuracy of 0.13 dB. The Cassiopeia A drawback for routine WSR-88D measurements is its low output level that requires long integration dwells.

Though Pratte and Ferraro (1995) and Sirmans and Urell (2001) describe the utility of the sun as a transfer standard for radar antenna calibration, there remains the fact that the sun is the least stable of the blue-sky noise sources, though it is the most intense. The solar signal is arguably not constant. Pratte and Ferraro (1995) suggest a “practical” standard uncertainty of 0.7 dB using SFT in network with reasonable process control. Sirmans and Urell (2001) suggest a “limiting” 0.44 dB standard uncertainty. Using sun flux transfer as an automated transfer agent having less than 1 dB reproducibility for the receive side should be maintained as a key calibration aid for the WSR-88D. The practical difficulties with using the sun as a source at the sub-dB accuracy level are four: (1) extended source deconvolution, which is problematic if the exact antenna and source pattern are not known; (2) the solar flux and blue sky sampling problems at the time of the measurements, (3) translation of the solar observatory reference measurements into time-adjusted, frequency-shifted, quality-checked solar flux values; (4) the techniques are radiometric in that they are only receive and thereby capable of checking the system “end-to-end” only by inference. Pratte and Ferraro (1995) suggest that an uncertainty contribution of 0.3 dB be attributed to the first three three issues in quiet sun years. Problem (2) is minimized by sampling the sun when its local elevation exceeds 20 degrees. Sample of the blue-sky flux can be taken several beam widths away from the sun position. Furthermore, the WSR-88D samples the sun by scanning through the source in elevation and in azimuth. Problem (3) is especially evident if the incorrect series of adjusted solar fluxes are used.

The WSR-88D vendor has supplied initial Sun Check software. This software and associated procedures have been updated by the WSR-88D Radar Operations Center and the Sun Check is a current element in the system calibration procedures. Certain procedural changes, software changes, and data communication changes may be employed to achieve the desired level of variance and quality control. The present version of Sun Check permits manual entry of system gain change resulting from a single experiment. Although current procedures call for repeated on-site measurements before technicians alter system gains, there are no convenient process control tools, and cases have occurred where technicians have altered system calibrations based on one or a limited number of sun scans.

The use of alternative sky sources, such as the moon or Cassiopeia-A, may be warranted for comparison, since the flux values of these alternate sources change so little over time. Guidice and Castelli (1970) provide details for use of these alternative noise sources. Daywitt (1984) provides an outline to use the moon as a noise flux source.

4.4. Lunar Reflections

Though an unknown RCS, the moon provides a variation of the engineering calibration with an unknown-but-repeatable target of opportunity. Many of the economies of the solar flux transfer measurement follow to the lunar reflection method: (1) a precisely calculable position, (2) a slowly moving target, (3) a visible target from all locations, and (4) full automation of the data collection phase. Furthermore, the advantages of the orbiting sphere target also apply to the moon. The drawback, however, is low signal-to-noise ratio that may be overcome by long integration times and an appropriate echo model. In the absence of placing a reflector or transponder in orbit, the moon is the lone two-way common target that might satisfy the reproducibility requirement among sites.

Active illumination of the moon may require frequency/time coordination among WSR-88D sites but this synchronization is easily satisfied using modern timekeeping.

4.5. Airborne Transponder

There are several techniques for using a distant transponder as an engineering calibration aid. The time-delay or frequency-shift transponder could be airborne in the atmosphere, orbiting in space, or mounted on a ground based high tower. A transponder "echo" signal is usually modulated to be distinct from the tower or vehicle echo echo. A number of transponder configurations are possible. Two types are considered in here. Figure 21 shows the so-called "bent-pipe" or linear coherent transponder. This device captures, amplifies and re-transmits the original, but modulated, radar pulse. Figure 22 shows a regenerative pulse delay transponder or active-radar-calibrator. With this device, a received pulse triggers generation of a new RF pulse created locally by a source. The regenerative transponder is similar to the radar test set in Figure 19 except that it is a remote device that would incorporate the WSR-88D antenna/radome contribution to the system calibration.

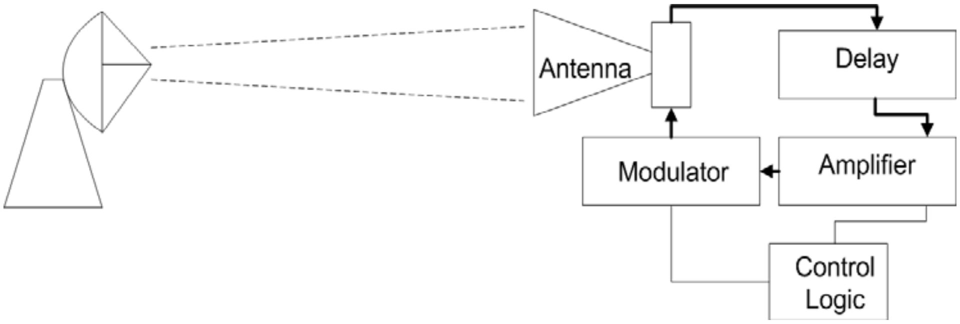

Figure 21 – The bent-pipe linear coherent transponder or active radar calibrator (RF paths in bold).

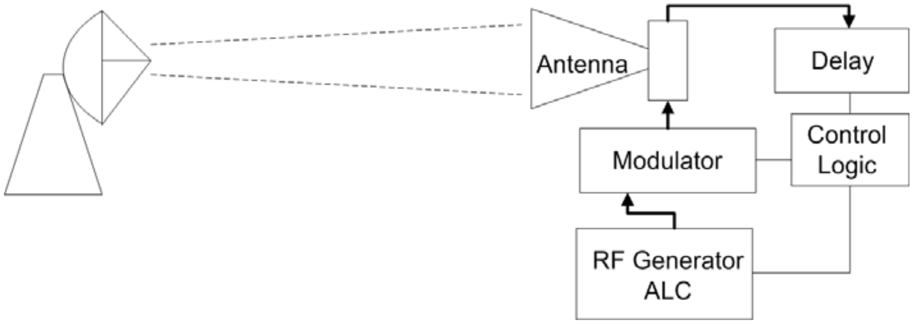

Figure 22 - Regenerative Pulse-delay Transponder (RF paths in bold).

A small transponder package can be lofted by a small fixed-wing aircraft, helicopter, or unpiloted controlled platform. Atlas (2002) mentions such applications. The aircraft platform raises the terminal to a height such that ground effects are minimized. There is much flexibility in this approach since optimum ranges, angles, orientations, and polarizations are possible. Aircraft rental, though not prohibitively expensive, places attachment constraints on the instrument package that must be designed and constructed to demanding flight requirements. As with any transponder, it is periodically re-calibrated. Remote control of the transponder would permit the operation by a single radar technician, and remote piloting of the vehicle (RPV) would reduce the need for aircrew and ground support.

The development of a small transponder package for a small aircraft would probably be less expensive than that for a RPV because an increased degree of miniaturization may be required for the latter. While we believe this approach has great merit, as does the orbiting transponder, we believe that the development schedule is much longer and costs higher those other approaches.

4.6. Orbiting Transponder

A satellite-borne weather radar calibrator would be an engineering calibration aid that supports international radar-hydrologic studies. As noted earlier, volumetric comparison of reflectivity from precipitation-of-opportunity, while a calibration monitoring technique in itself, has noted reflectivity biases of up to several dB from calibrated weather radars. The use of an orbiting radar, such as from the Tropical Rainfall Measurement Mission (TRMM) or future programs, for “meteorological calibration” comparisons reduces one of the components of variation, but requires essential assumptions about wavelength translation, aspect, and effective pulse volumes, which need to be validated. As noted, the TRMM precipitaion radar is itself calibrated by use earth-based transponders.

In lieu of this, an active or semi-active transponder as a calibration aid would be an outstanding package for an orbiting earth resources satellite or perhaps the International Space Station. Meteorological radars have long desired a common, repeatable calibration target to bring precipitation measurements worldwide into conformity. A radar transponder specified to return a calibrated signal proportional to the received pulse amplitude and on the interrogating radar’s assigned frequency.

Ten watts from 400 km range can produce a 30 dB SNR for most weather radars. It could be defined designed to provide usable return to coherent (klystron or traveling wave tube transmitters) and with more difficulty noncoherent (magnetron transmitters) weather radars. The satellite infrastructure would provide power and communications. Carrier frequency, ranging codes, transponder delays, echo bandwidth, and output power could be adjusted by a command and control data link. An engineering model of the instrument could be flight tested from a high altitude aircraft. Satellite transponders designed for communications are available in the microwave bands. A low power device might have a 5 watt CW RF output, weigh less than 1 kg, and consume 20 watts from the power bus exclusive of antenna. With an adequate antenna this RF power would provide sufficient margin from low earth orbit.

The Mile High Radar experiments in 1995 and range calculations suggest that the radar calibration spheres in orbit today present too small a RCS to be used by the WSR-88D and other weather radars. Finding and tracking satellites was accomplished with a capable pedestal controller and orbital prediction software. The issue is sufficient SNR. At an 800 km orbital altitude a RCS of 100 square meters would provide a per-pulse SNR of 10 dB, which may be usable as a calibration aid. The RCS efficiency of a trihedral retro-reflector, which could yield such a RCS, is much greater, but the device requires attitude stabilization. No orbiting calibration aids can supply this large RCS.

Hildebrand (2004) provided the following perspective for getting an active weather radar calibrator into orbit. To orbit a device, payload characteristics and support requirements will need to be worked out. The radar calibration instrument details including size, weight, power consumption, pointing angle accuracy requirements need to be developed. One must describe the RF characteristics that will exist including radar power and frequencies received and transmitted, any issues relating to EMC that may exist, and anything of operational importance relating to command and control. One must also explain the need for being able to see the target in terms of local geographical and the desired repeat frequency.

This information will enable an evaluation of what this would look like as a stand-alone mission or as a piggyback to some other mission, possibly including the space station. At this point, the needed information for a formal instrument evaluation and preliminary mission design will be available. These activities can be performed at specialized laboratory facilities at NASA Goddard Space Flight Center.

4.7. High-Tower Transponder

Use of elevated (tower-mounted as in Figure 12) ground-range measurements as engineering calibrations require wideband path characterization, or one must attempt to analyze multipath and minimize the stationary multipath. Given a simple propagation model and a well-behaved path, it could be possible to use a spatial interferometer technique to assess the main beam path loss, while making reasoned assumptions about terrain scattering coefficient. For a vertically-translating interferometer reduction to provide the required accuracies, the reflection model must be nearly exact.

An alternative to the interferometer analysis is to position the transponder at a height where multipath is minimized. An open site is required. Based on the two-ray model covered earlier, the lowest optimum height is achieved where the angle of the first pattern null conforms to the reflection angle. Though the required open terrain geometry and the real estate and can be found at many sites, others will be very difficult. It would be helpful to more conduct experiments of the above type using a hydraulic tower to raise and lower the source over a range of say 50 meters to deduce propagation path behavior.

Real-time methods have been proposed to delineate reflected from direct echoes, such as the invention of Alon (2002), but these depend on a large path difference relative to the resolution cell. It is possible to measure the individual returns to resolve the channel impulse response by ultra-wideband methods (Kim 2004). However, these approaches exceed the intrinsic bandwidth of the WSR-88D and appear to require considerable additional investigation. Transmitting several measured CW tones, or a swept carrier, across a significant frequency band permits channel sounding by differential measurements of received power. But this method like the UWB schemes will likely exceed the bandwidth of the WSR-88D antenna for the delay resolution needed.

From the two-ray model the measured path loss can vary from the free space path loss by as much as +6 dB to less than -20 dB. The varying lift height over several interference cycles can be analyzed if a suitable reflection model can be found. In general the behavior will be different for vertical polarization than for horizontal, and significantly different if multiple reflecting surfaces are illuminated. The height gain curves from Figures 14 and 15 show that either the path loss will be overestimated or the antenna gain will be underestimated. This has been the experience of the CHILL staff over many repeat calibrations from ground-based terminal locations. We estimate that a probable error in judging free space loss from terminals near the ground is about 2 dB. Our CSU-CHILL experiments suggest that by selecting the correct tower height to maximize antenna isolation, for example 15 meters or more, the radar-to-terminal loss approaches free space terminal.

For many years weather radar operators have employed the two-way response of fixed tower targets to confirm power and angular calibration reproducibility. The intent was to guard against significant system changes that may otherwise go unnoticed until the system was needed for severe weather. Experience with these checks suggests that the variance of two-way path loss may greater than the 1 dB except on the most optimum paths. Part of the variation was from the path and part from varying tower cross section. Evans (1990) discussed the issues associated with establishing an antenna range, which we are essentially attempting with a ground-based terminal, including use of fencing to minimize ground reflections. Far-field ranges, compact ranges and near-field ranges may have application to the development of a WSR-88D calibration aid; however, our experience is that both the far-field and compact ranges entail off-site towers and unknown real estate issues at most locations.

4.8. Calibration Process-Monitoring and Management Software

The conventional purpose of process monitoring and control is to detect abnormal “plant” changes and to alert operators of such. Plant managers and engineers have long recognized the value of collecting and analyzing performance and environmental data from machinery and processes. Armed with such data, they regulate plant efficiency, utilization, and throughput. When processes go awry, corrections are made to minimize downtime, often before the process has actually failed. The goal of process monitoring is to capture as much data as possible on a timely basis. This data is then displayed and analyzed to "verify" or to “tune” the manufacturing process.

Though not a calibration device per se, process-monitoring software is an engineering calibration aid fundamental to an automated approach to managing quantitative calibration data and would be applied to all the techniques. It could display and analyze engineering and meteorological calibration data for a site or sites over time. Such software can detect changes in process variance relative to past calibration data for “baselining”. It gives radar technicians and engineers the ability to develop insight into calibration problem solving and prevention. The performance database could, for example, consist of real-time housekeeping variables, adaptation data, and log/data files generated by the calibration aids discussed in this report, plus environmental data from additional sensors.

5. Comparison Matrix of External Calibration Aids/Options

In comparing ideas and possible schemes for external calibration aids, we considered their “complexity”, “externality”, “independence” and “applicability to future enhancements” (dual polarization for example). Process-monitoring software allows analysis of calibration-related performance data from the radars. It will be a major factor in the successful implementation and automation of any external network calibration methods. Since process-monitoring software supports all engineering and meteorological calibration methods, separate scoring for this calibration aid was not conducted.

For this report we focused on potential development of eight engineering methods: Process Monitoring, External Test Set, Drifting-Sphere, Near-Field Pattern Measurement, the Enhanced Sun-Scan, High-Tower (elevated ground range) Transponder, Airborne/Orbital Transponder, and Lunar Reflection.

Table 3 attempts to quantify the relative advantages and disadvantages of each device idea/method against several criteria. For each criterion, the six ideas are rank ordered using a numerical scale of 0 to 6, with 0 being the least desirable and 6 being the most desirable method rated against the criteria. In theory, this would yield insight into the optimal solutions, with the highest score indicating the best of the considered solution. In practice however, this method merely serves to separate potentially viable solutions from the impractical or ineffective. The rankings are in the final examination, subjective.

In Table 3 all criteria have an equal effect on the summary ratings, though some criteria may be more important to system managers than others. However, from examination of the results of Table 3, one observes that three methods are clearly separated from the others in relative merit: External Test Set, Drifting Sphere, and Enhanced Sun Scan. We strongly recommend enhancing the solar flux measurement through process monitoring: software modification, increased automation, improved data management, and quality control of system parameter changes. In bypassing the Sun Flux enhancement for the recommended list, we include the exploration of a Near Field Pattern method, because it has potential for a major engineering calibration advancement. Conversely, the least effective and desirable is the airborne transponder for reasons related to complexity, cost, and operational considerations. Note that the near field technique and the high tower transponder are ranked about equally as each has merit but carry with them some important issues relating to accuracy, cost and practicality.

Comparison Matrix of External Radar Calibration Options for WSR-88D							
Relative grading scale 0 to 6 (least to most desirable)							
	External Test Set	Drifting Sphere	Near-Field Pattern	Sun Scan (enhanced)	High-tower Transponder	Airborne Transponder	Lunar Reflection
Future System Compatibility (ORDA, Dual Pol)	4	6	3	5	2	0	1
Traceability Independent of Radar System	5	6	4	3	2	1	0
Potential Ease, Frequency of Use	4	5	2	6	1	0	3
Minimum Development Required							
Hardware	4	3	2	6	1	0	5
Software	6	2	5	4	1	0	3
Interface and Installation (including remote item)	4	5	3	6	1	0	2
Site-to-site Repeatability	6	5	3	4	1	2	0
Economical to execute	4	3	2	6	1	0	5
Automation rating	3	4	1	6	2	0	5
Portablility	4	5	2	6	1	0	3
Minimum Staff training required	3	4	2	6	1	0	5
Lack of much operational operational Outage	4	5	1	6	3	0	2
Absence of Real Estate needed	4	3	2	6	0	1	5
Two-way (Inclusion of transmit as well as receive)	3	6	1	0	5	4	2
Measures ranging errors, high accuracy	4	6	1	0	3	5	2
Measures dynamic pointing accuracy	1	3	0	6	5	4	2
Amenable to Statistical Process Control	6	4	3	5	1	0	2
Relief from reference point translation	3	6	1	0	5	4	2
Acceptable to the community	4	5	3	6	1	2	0
Compatibility with other weather radars (TDWR)	0	6	5	4	2	1	3
Subsystem calibration rating							
Antenna/Radome	0	6	4	5	3	2	1
Receiver/Processor	6	5	0	4	2	3	1
Transmitter	5	6	1	0	2	4	3
Summary of Ratings	87	109	51	100	46	33	57

Table 3 – Comparison of External Device Engineering Calibration Aids. Calibration process monitoring capability is assumed.

6. Selected Engineering Calibration Aids

This report asserts that any given method will not by itself provide calibration to the required 1 dB reflectivity uncertainty. Calibration of a complex RF instrument proceeds piece-wise until the entire assembly is deemed calibrated. There should exist a test suite of reproducible, low-variance checks on the calibration state of WSR-88D radars. Effort should be expended in incorporating selected “engineering calibration” and “meteorological calibration” aids into the test suite.

Objectives for the members of calibration test suite are as follows: First, it must reduce the network’s power channel(s) calibration error (reproduce) and inspire confidence. Second, it must provide means to monitor and maintain the calibration process. And it must mesh with the existing electronic build-in calibration scheme. Third, it should improve antenna pattern characterization. Future modifications to the antenna (dual polarization) will create an increased need to field check antenna performance. The dual-linear polarization feed horn change proposed for the WSR-88D should be checked for polarization orthogonality/isolation as well as end-to-end radar calibration for each channel. If available, calibration aids could be used for optimizing the feed position and for measuring sidelobe levels and cross polarization isolation. Fourth, calibration aids should verify dynamic end-to-end antenna-pointing accuracy.

To achieve Sirmans’s 0.6 dB (Sirmans 1992) standard instrument uncertainty through engineering calibration, automated techniques are needed to improve reproducibility, to increase the re-measurement frequency, and to minimize human and implementation errors (blunders).

In the development of a proposed scheme, there are technical hurdles in hardware, software, and interfacing. We expect that any technique will require supporting "test" software for the WSR-88D. There are also logistics and resource challenges after the development including field test phases, training, real estate, and operational downtime.

Verifying and maintaining calibration in the WSR-88D network may go beyond identifying a single technique that will administer the calibration "fix", but rather the diligent application of a proven test suite, based on different approaches that measure the radar in its entirety, that is "end-to-end" and with as few assumptions as possible. Of the recommended engineering calibration aids in the test suite, the independent test set appears to provide the most cost-effective and straightforward means to eliminate assumptions about the electronic calibration. In conjunction with the test set, the drifting sphere method offers the best opportunity for a reproducible, end-to-end external calibration check with the WSR-88D.

The near-field pattern technique is of renewed interest. A decade ago, the art and engineering of precisely positioned scanning was not possible outside the laboratory. With the advent of the laser tracker and refined spherical near-field compensation techniques, we believe the method should be seriously evaluated for the WSR-88D. With it we should be able to measure detailed far field co- and cross-polar antenna patterns and readily compare changes to the radar system.

A process-monitoring system will assist managing more than 60 adaptation data points for the engineering calibration. The level 2 housekeeping contains critical site data that can be used to track and maintain the radar system given good process control tools to view trends and correlations and track changes. The tools may be web-based.

The class of radiative flux methods is excellent for calibration aids. In time an enhanced solar flux method may be the frequent, on-line, long-term engineering calibration aid for the WSR-88D. Though the radiative flux transfer methods, especially the SFT, are the most cost-effective calibration checking, it is not presently an independent method, so any calibration error in the "critical path" will thus propagate to the antenna measurement.

Though the lunar reflection method needs more research and development than the radiative flux methods, it may prove to be the most economical "end to end" calibration aid. Limited results from the MHR suggest that reproducibility of RCS measurement to less than 1 dB is possible on the WSR-88D.

Requirements for calibration traceability are becoming more stringent because of the emphasis on automation in today's systems. Thus is would seem appropriate, if not required, to have a corresponding level of traceability capable of objectively evaluating the calibration of separate radar units. Calibration-management software is designed to control and collect data directly from an instrument, analyze test result data, and allow users to track calibration, status changes, reverse traceability, and corrective action histories by means of a relational database.

7. Recommendations for External Engineering Calibration Aids/Options

The following exploratory development efforts are proposed for improving WSR-88D network calibration through the use of external options, following customary engineering design review and documentation processes. These engineering calibration aids can be largely automated. Comments on requirements definition and development are included.

Proposal 1. Develop and demonstrate online **calibration-monitoring software tools**. These are the technical tools for managing calibration parameters and calibration data logged in the field.

Develop detailed requirements and preliminary software design
May be web-based
Access to archive level 2 housekeeping and adaptation data

Access to frequent solar flux transfer method logs
Access to source traceability data
Access to network reflectivity comparison
Calculate intermediate quantities as required
Permit additional calibration aids as developed, and other environmental sensor data
Each calibration aid must generate and log a report
Plot and correlate trends, histograms, and scatter diagrams
Tools to evaluate outliers and error levels

Proposal 2. Develop and demonstrate a prototype **calibration test set** for the purpose of independent verification of the calibration of transmit, receive and antenna subsystems.

Develop detailed requirements and the radar interfacing and modification protocol
Develop dual polarization modifications to the WSR-88D calibration process
Develop engineering design standards and techniques
Identify working calibration standards and traceability
Develop test plan for independent radar test set
Measure receive/processor gain on multiple waveforms (e.g. CW, delayed pulse, noise)
Measure peak transmit power and pulse width
Attempt antenna gain using independent solar flux transfer method (optional external LNA)
Design for mechanical balance
Measure/calculate system calibration constant
All measurements must be independent of radar calibration sources and state
Integrate commercial communications and test equipment
Develop supporting test software for the WSR-88D
Include measurement redundancy to reduce number of trials

Proposal 3. Develop and demonstrate a **drifting-sphere calibration** method for the WSR-88D for the purpose of complete end-to-end radar verification.

Develop detailed requirements and radar interfacing and modification protocol
Identify working calibration standards, traceability for a dual-polarization WSR-88D
Develop engineering design
Target tracking to an error less than the intrinsic WSR-88D angle/range uncertainty
Confirm 2-way RCS measurement to within 1 dB reproducibility across network.
Characterize a dual linear polarization antenna pattern to include first sidelobes and cross-polar isolation to (-30 dB)
Resolve how to “keep target centered”
Employ as close to a fundamental calibration standard as possible
Measure/verify target RCS
Analyze for dynamic positioning hysteresis in base data
Develop supporting test software for the WSR-88D
Develop balloon package
Develop theoretical sampling model

Proposal 4. Develop and demonstrate an in-situ, **near-field antenna pattern measurement** method for the WSR-88D. Knowledge of the dual polarization antenna pattern is a desired outcome.

Develop antenna pattern uncertainty budget from knowledge of near-field techniques and WSR-88D mechanical details
Implement probe antenna configuration and acquisition hardware, and near-field analysis software to field-test a near-field method
Develop engineering design
Develop supporting near-field test software for the WSR-88D
Measure mainbeam gain on principal plane cuts to less than 0.25dB error

Characterize a dual linear polarization antenna pattern to include first sidelobes and cross-polar isolation to (-30 dB)

Proposal 5. Enhance the **solar flux transfer** method based on prior evaluations and recommendations (Sirmans and Urell 2000, Pratte and Ferraro 1995).

Develop detailed requirements and preliminary software design
Improve scanning for pattern fitting and dynamic pedestal alignment
Fully-automate original functionality to permit weekly remote operation
Develop method to synchronize solar flux methods among clusters of radar sites
Develop the calibration aid as source of trend data to be used by radar site staff
The implementation should check consistency of adaptation data
Check consistency of signal generators and source paths online
Explicitly calculate critical path and filter gains
Measure system figure of merit G/T
Measure solar flux itself
Remove alternative to modify site adaptation data
Logging intermediate data and final results
Implement tools to analyze the intermediate data and the results

Proposal 6. Develop and demonstrate a **high-tower transponder** method for the WSR-88D to the purpose of end-to-end calibration verification.

Develop critical requirements
Develop environmental packaging, support systems, and electromagnetic compatibility requirements
Develop transponder placement criteria
Develop engineering design
Develop engineering prototype

Proposal 7. Develop and demonstrate an **airborne or orbiting transponder** method for the WSR-88D to the purpose of end-to-end calibration verification.

Develop critical requirements
Develop environmental packaging, support systems, and electromagnetic compatibility requirements
Develop transponder vehicle interface criteria
Develop engineering design
Develop engineering prototype

Proposal 8. Develop and demonstrate a **lunar reflection** method for the WSR-88D as an end-to-end calibration aid.

Develop detailed requirements and preliminary software design
Develop weak-echo processing model
Extend the solar flux support software with lunar position
Implement support software and lunar acquisition tests for development data
Log intermediate data and final results
Implement tools to analyze the intermediate data and assess results

8. Concluding Remarks and Required Studies

This report is a working document for external weather radar reflectivity calibration aids, providing source material, survey, and feasibility evaluation. Over the months since this study began, new and old ideas have been evaluated, and former approaches reconsidered. External "targets", whether test targets from independent generators, or physical targets located away from the site, or opportune precipitation targets, play an important role in calibration, because they provide a core test suite for technical staff to improve reproducibility and build confidence in calibrations. The schemes in combination must be practical, automated, and provide rigorous field calibration of system elements. For discussion purposes, calibration aids have been divided into "engineering calibration" aids and "meteorological calibration" aids. Engineering calibration aids have been the focus of this report and its recommendations. The most feasible meteorological calibration aids are reflectivity comparisons, rainguage comparisons, and dual polarization consistency checks.

In facilitating this report the ROC recognized the difficulty-in-practice of network calibration, but emphasized the importance of addressing the reflectivity calibration challenge again. This report answers the challenge with what has changed in industry since the last time this problem was reviewed, and what could be accomplished in the near-term to improve reflectivity calibration. Recent events demonstrated that even with the internal closed-loop calibration-maintenance system, radars might still be out of calibration by a few dB without generating alarms. Furthermore, persistent biases in reflectivity factor among WSR-88D clusters have been noted.

The external radar calibration aids described here require challenging development and integration. The recommended four are the most feasible. Atlas (2004, 2002) remarked that Dr. Merrill Skolnik of the Naval Research Laboratories is skeptical about the accuracy that may be "achieved" by radar calibration techniques. The ongoing premise is that with thorough testing, carefully designed and executed test suite, in practice, will yield the WSR-88D goal of 1 dB instrumentation reflectivity uncertainty. The importance of external calibration aids is increased by the differential calibration requirements of dual polarization sensing. Future studies can explore alternate techniques and calibration issues. Lunar calibration method has already shown promise with NEXRAD radar. The solar flux technique can be enhanced. Of residual on-site equipment (instrument) issues, variable radome loss from moisture and aging has been reduced by actively maintaining the environmental coating. However the radome attenuates significantly in heavy rain events and this adjustment will need to be dealt with eventually.

No one external calibration aids will calibrate the WSR-88D. Calibration of a complex RF instrument proceeds piece-wise from fundamentals until the entire instrument is deemed calibrated. The goal is set of several common, reproducible, low-variance checks the on the calibration state of the radars in the network. Automation of the measurement phase of a calibration minimizes staff resource and errors. For example, solar flux measurements could, and should, be acquired daily, for calibration post-processing.

Of the many specific calibration ideas, schemes, techniques, and methods, perhaps the most exciting new subject is in near-field antenna pattern measurements, applied in-situ to large operational antennas. Applicable advancements over the last decade were also found in GPS universal timekeeping, significant RCS measurement improvements for dynamic drifting-spheres, improved computing, and high capacity data telecommunications, and test equipment (Hefman 2004). Another promising scheme is the use of ultra-wideband waveforms to equalize the RF channel impulse response for fixed ground-range terminal measurements. However, a UWB method appears to require considerable advanced development.

An "absolute" instrument calibration of the WSR-88D is important for the hydrology mission. It is generally agreed that the technical level of hydrology and water management disciplines could profit from improved Z_e accuracy from the WSR-88D network today, if available, and the ROC wishes to know when the point of diminishing returns of calibration effort is reached. Standards traceability and process monitoring will provide the basis on which this can be known.

Direct support for system enhancements such as open system processing and dual polarization was stressed in this report. At this writing, WSR-88D differential (dual polarization) reflectivity "engineering calibration", and differential "calibration-maintenance", remain issues without consensus. At the design stage, the cost of hardware and software for improved primary calibration and for differential will be negligible compared to the costs of managing engineering change proposals and retrofits later. In fact, well-designed and implemented calibration methods can support WSR-88D upgrades. For example, it would be advantageous if the antenna subsystem could be checked, before and after dual-linear polarization (feed horn and other devices) change, for changes in pattern, and polarization isolation, and well as end-to-end radar calibration.

In this report the development of apparatus for the independent radar test set, the drifting-sphere method, and the near-field pattern measurement are strongly recommended. The promising near-field, in-situ scheme for large antennas should be evaluated for WSR-88D feasibility. Calibration-oriented process-monitoring software and adjunct databases are required. The development of approaches may involve limited hardware, software and procedural modifications to the WSR-88D, and should go along with the development of dual polarization modifications and with the existing built-in test and evaluation (BITE) functions.

Near field patterns are the most promising new approach to calibrating large antennas in the field. There is a large potential payoff here if a practical application can be developed.

A matrix was generated that compared eight calibration ideas selected for the WSR-88D. Four are recommended for near-term feasibility study and preliminary design. Each has the potential to improve dual polarization reflectivity modifications. The development of process-monitoring software was deemed so important that its scoring was omitted from the martix.

Computerized calibration process-monitoring
Independent radar test set method
Drifting sphere method
Near-field antenna pattern method

The four recommendations offer an opportunity to have a test suite of practical engineering calibration aids after a reasonable development cycle. The recommended approaches keep risks bounded and minimize utilization costs.

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This report was written to satisfy a “short-fuse” requirement for a current survey of external calibration techniques for the WSR-88D. Considerable revision has been made to the originally-submitted version at contract time. The authors believe that the survey is exhaustive, perhaps excessively, but answers the questions posed by the ROC. However, practical exacting calibration of weather radars is a multifaceted effort that is art and science. To help categorize various approaches the authors coined usage for the terms “engineering calibration”, “meteorological calibration”, “calibration-maintenance”, “internal”, “external”, and “independent”. In grappling with the current WSR-88D engineering calibration picture, we believe we have arrived at four engineering calibration aids to be developed and noted important caveats and design parameters for development of these four recommendations.

Furthermore, seven recurrent themes developed during the study. First, computerized process monitoring and management of reflectivity calibration is surely required for exacting calibration of a large radar network. Second, the categories “engineering calibration” and “meteorological calibration”, and the distinction between “absolute” (basic calibration) and “calibration-maintenance” has helped keep things on track. Third, automation of calibration aids is definitely required. Fourth, expect each calibration aid will need some kind of supporting online or offline software. Fifth, the engineering calibration issues must be included in the design of the dual polarization upgrade. Sixth, external calibration aids should be independent of each other and independent of built-in test and evaluation functions. Seventh, design reviews should be required for proposed engineering calibration aids and for system redesign that is associated with calibration.

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Appendix A: Commercial Products

This listing typifies products for continued exploration of calibration potential. The appearance of company names below is random. RSIS, NCAR, nor the US government endorses the following products:

Radar Specialty Measurement Companies

Raytheon Technical Services
Manager, Metrology Operations
720.200.1407 Phone
720.200.1410 Fax

Intersoft Electronics NV
Lammerdries 27
B-2250 Olen
Belgium
Phone: +32 (0)14/23 18 11
Intersoft Electronics USA
850-678-0777

System Planning Corporation
1000 Wilson Boulevard
Arlington, VA 22209-2211
(703) 351-8200

Airborne and Orbiting Transponders

Herley Industries, Inc.
101 North Pointe Boulevard
Lancaster, PA 17601
Phone: (717) 735-8117
Fax: (717) 397-9503

Alcatel Espacio
C/ Einstein, 7 (PTM)
28760 Tres Cantos (Madrid)
ESPAÑA
34 91 807 7900

AeroAstro, Inc.
20145 Ashbrook Place
Ashburn, VA 20147
Phone: 703.723.9800
Fax: 703.723.9850

Radar Calibration Targets

Spectrum Technologies International, Inc.
P.O. Box 1328, Grand Junction, CO 81502
(970) 243-2925

Trimillennium Corporation
P.O. Box 1328
Grand Junction, Colorado 81502-1328 U.S.A.
970.243.2897

Cuming Microwave Corporation
225 Bodwell Street, Avon, MA 02322
Tel: 508-580-2660, 800-432-6464

Damaskos, Inc.
PO Box 469
Concordville, PA 19331
(610) 358-0200

Rozendal Associates, Inc.
9530 Pathway St., Suite 101
Santee, CA 92071
(619) 562-5596

Universal Metal Spinning Company
1301 Broadway Blvd NE
Albuquerque NM 87102
505 / 242-2650

Ultra-wideband Equipment Vendors

Ultra Wideband Working Group

Multispectral Solutions, Inc.
20300 Century Boulevard
Germantown, MD 20874

Picosecond Pulse Labs
2500 55th Street
Boulder, Colorado 80301, USA
303-443-1249

Time Domain Corporation
Cummings Research Park
7057 Old Madison Pike, Suite 250
Huntsville, AL 35806
256-922-9229

Freescale Semiconductor, Inc.
6501 William Cannon Drive West
Austin, Texas 78735

Microwave Test Equipment

Test and Diagnostics Consortium (TDC)

LAN Extension for Instrumentation

Aeroflex, Wichita Division
10200 West York Street
Wichita , KS 67215
316-522-4981, 800-835-2352

DRT, Inc.
20250 Century Boulevard, Suite 300

Germantown, Maryland 20874
301.916.5554

Tektronix USA
800-833-9200

Agilent Technoligies, Inc
800 829 4444

Giga-tronics Inc
4650 Norris Canyon Road
San Ramon, California 94583
800 726 4442

Boonton Electroniccs
25 Eastmans Road
P.O. Box 465
Parsippany, NJ 07054-0465
973-386-9696

Near-Field Measurements

Nearfield Systems Inc.
19730 Magellan Drive,
Torrance, California, 90502 USA
310-525-7000

ORBIT/FR, Inc.
Horsham, PA USA
506 Prudential Road,
Horsham, PA 19044
215-674-5100

The Howland Company, Inc
4540 Atwater Court, Suite 107
Buford, Georgia 30518
678-546-5680

Microwave Instrumentation Technologies
M I Technologies
Suwanee, Georgia 30024
800-854-3660

General Measurements

NCSL International
2995 Wilderness Place, Suite 107
Boulder, Colorado 80301
303-440-3339

Appendix B: WSR-88D Specifications

For designing calibration aids for the WSR-88D weather radar, the following specifications and radar characteristics may be useful.

Antenna characteristics
Type: center fed paraboloid of revolution 28 feet in diameter.
Frequency range: 2700 - 3000 MHz.
Polarization: linear horizontal.
Gain at 2850 MHz: 45.5 dB (including radome loss).
Beamwidth at 2850 MHz: 0.925 deg.
First sidelobe: -29 dB (others less than -40 dB beyond 10 deg).
Radome two-way loss: 0.24 dB at 2850 MHz dry.
Radome: 38.75 ft equatorial diameter, 34.8 ft height, 23.2 ft base circle; hexagonal and pentagonal panels bolted panel-to-panel through reinforced edges; fiberglass-reinforced polyester laminate, polyurethane core.
Elevation coupler 2DC1: 44.2 dB ± 0.3 dB, variation over frequency ± 0.2 dB; 25 dB minimum directivity.

Pedestal
Type: Elevation over Azimuth

Pedestal Function	Azimuth	Elevation
Steerability	360 deg	-1 to +45 deg
Normal Scan	360 deg	+0.5 to +19.5
Max rotation rate	30 deg/sec	30 deg/sec
Min rotation rate	0 deg/sec	0 deg/sec
Acceleration	15 deg/sec^2	15 deg/sec^2
Mechanical Limits	360 deg	-1 to +60 deg
Positioning Error (max)	+/-0.2	+/-0.2

Transmitter
Type: S-band, coherent chain, line modulator, klystron amplifier (53 dB gain typical).
Frequency: 2700 to 3000 MHz.
Power: 750 kW peak at klystron output.
Transmitter to antenna loss: site dependent, 2 dB typical.
Average Power: 300 to 1300 watts.
Pulse Widths: 1.57 and 4.5 microseconds (-6 dB points).
PRF short pulse: 318 to 1304 Hz.
PRF long pulse: 318 to 452 Hz.
Phase noise (system): -54 dBc required, -60 dBc typical.
Short pulse spectrum:-40dB at +/-12.4MHz,-80dB at +/-62MHz -80dB at +/-19.6MHz congested area filter.

Receiver
Type: Coherent with instantaneous IF automatic gain control.
Dynamic signal range: 95 dB
Intermediate Frequency: 57.55 MHz.
3 dB bandwidth: 0.630 MHz.
6 dB bandwidth: 0.798 MHz.
System noise figure: 4.6 dB (540 Kelvin).
Receiver Noise: -113 dBm.
Front end interference rejection filter: 0.5 dB at +/- 700 kHz, 30dB at +/- 50 MHz, 60dB at +/- 200 MHz.
Pulse interference censoring: log amplifier/detector.
Receiver protector 2A3: coupled path for test signal injection (J3) -20 dB calibrated to ± 0.2 dB.

Signal Processor
Sample interval: 1.66 microseconds.
A/D Number of bits: 12.
Clutter Filter: infinite impulse response (5 pole elliptic).

MTI: 30 to 50 dB, user selectable.
Notch half width: 0.5 to 4 m/sec.
Base data range increment: 250 m.
Base data azimuth increment: 1 deg.
Base data numerical precision: 0.5 dB (reflectivity).
Calculated system sensitivity: -8 dBZ at 50 km (-42 dBZ @ 1 km)

Other Mechanical
Tower platform height: 5 to 30 meters.
Reflector offset from the rim of the dish to feed horn: 5 ft 10 in.
Upper stops: 60 degrees (could be removed for testing and the antenna "bird bathed").
Lower stops: -4 degrees (must maintain clearance between the reflector and the platform).
Dish edge to radome clearance: 18 inches at reflector bottom in the near-horizontal position
Dish edge to radome clearance: 24 inches at reflector top where retractable ladder extension installed.
Centerline height of antenna: 15 ft above the platform in near-horizontal position.
Feed assembly clearance: 31.8" from radome wall in near-horizontal position.
Ladder assembly clearance: 29" from radome wall in near-horizontal position.
Vertical rotation axis (azimuthal centerline) to the face of the reflector: 5 ft 2 in.
Face of the reflector to the outside edge of the feed assembly: 12ft 10in.
Centerline offset of antenna: 5.8in below radome equator.
Back of feed assembly to the radome wall: increases with elevation angle.

END OF SURVEY REPORT