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SUMMARY OF THE RADAR CALIBRATION WORKSHOP

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Introduction

Radar calibration is one part of producing high quality data. It has been almost 25 years since the last workshop on this topic was held. Since then, there have been a many changes in the field of weather radar. We now have operational Doppler, wind profiling networks, research polarisation and bi-static radar systems. Computing, telecommunications and digital technologies have changed dramatically. There are also many new parameters that are now estimated such as Doppler radial velocities, various polarisation parameters and even the refractivity field. The radar data are also collected from a variety of platforms including ground, sea, air and space.

Calibration procedures and techniques have fallen into the realm of ideology, some into myth while others have been routinely adopted into practice. Traditionally, calibration refers to measuring the radar characteristics, determining the conversion from power received to reflectivity factor and to assessing pointing accuracy. However, depending on the application, calibration has come to include includes real-time fault monitoring, validation and adjustment. At the end of this chain of categories, there is also issue of data quality, which also includes issues of signal processing, clutter filtering, scanning strategy, attenuation and even radar siting.

It is difficult to be categorical with the definitions as the boundaries are fuzzy and there are many options in sorting out the problems. Where is the boundary between the receiver and the signal processor in a digital system? Is calibration finished after the receiver transfer function is measured, after the 'best Z' is determined or after the 'best R' is estimated? What was clear from the meeting that what we mean by calibration was 'fuzzy'.

From an applications or end user perspective, radar calibration is seen to be tightly intertwined with radar validation. Most often, the user is interested in rainfall rate or amount and while the radar may be 'well calibrated' electronically, the validation of the radar rainfall derived data is 'the' issue.

A specialty meeting was held on the topic of radar calibration at Annual General Meeting of the American Meteorological Society in Albuquerque, New Mexico, 13-14 Jan 2001. The objective was to review pertinent subject matter related to radar calibration with a focus on operational field systems. This paper presents a summary of the 30 workshop presentations. As the planning of the workshop evolved, the expanded view of 'calibration' became evident.

The workshop was broken down into five topic areas: System overviews, Components, External Calibration, Advanced Techniques, and Validation Issues.

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Definitions

The field uses the word calibration both in a specific and a generic sense. Paul Smith began the workshop with an overview of what is traditionally meant by calibration and performance monitoring. He defined the specific terms.

> ***Calibration*** *is the measurement of system characteristics, which enter into the determination of observed quantities.*[1]
>
> ***Performance Monitoring*** *is the verification that other system characteristics are within acceptable limits.*

An important aspect is an estimate of what is limit of achievable calibration. He presented the following table.

Table 1: Calibration Uncertainty Estimate

Source	Uncertainty Estimate
Sampling	1 dB (or more)
P_{sg}	1 dB (1.5? 2.5?)
G_h^2	0.6 dB
Filter Loss	0.5 dB?
Θ,Φ	0.3 dB each
Combined	**1.7 dB**

System Overviews

Tim Crum of the ROC described the improvements in all calibration aspects of the WSR-88D system - these include procedural as well as technical and scientific. They have incorporated the Sun as a test signal source and they evaluate the success of their network calibration through raingauge comparisons. The solar calibrations showed an overall bias of -1.47 dB and demonstrated improved precipitation estimates.

Chris Clarke of the UKMO showed how fixed structures in the vicinity of the Chenies radar could be used to monitor the end to end calibration. They found that radar/gauge comparisons vary too much (10-15%) to monitor the health of the radars. With the clutter target technique, they found that their hardware was stable within 6% or 0.25dBZ. It is not clear whether opportunistic or installed ground targets would be useful for inter-radar comparisons.

Having moved radars all over the worlds, Jeff Keeler of NCAR, suggested that consistency in the calibration procedure is paramount, even to the extent of using the same test equipment and test personnel. Monitoring and tracking of the results was important to provide confidence that the calibration measurements were believable. This is a theme echoed throughout the workshop, you have to have enough information

[1] *This differs from the AMS Glossary of Meteorology (2nd Ed.) definition which is the process whereby the magnitude of the output of a measuring instrument (detected backscatter power) is related to the magnitude of the input force (radar reflectivity) actuating that instrument.*

to believe the measurements that you make otherwise systemic errors can arise.

Fran Hartwich of Raytheon described the Moving Target Simulator which is part of the TDWR calibration procedure. However, its use is somewhat limited since finding a good site for the device is limited by ground clutter and terrain obstruction considerations, another common theme in the workshop.

Radar Components

Chris Clarke of the UKMO described their fault monitoring system and how it helps them monitor the health of their radars. He demonstrated its utility in studying the reliability and longevity of their traditional versus their co-axial magnetron transmitters.

Gene Mueller of Aeromet, Inc. revisited the filter loss issue in light of the use of narrow filters. He simulated distributed weather signals, assumed a matched filter and looked at the signal loss after filtering and concluded that the average matched filter loss is ~1.8 dB. He promoted the use of the matched filter over narrower filters since there is an accuracy tradeoff.

With the advent of high speed A to D converters and Dusan Zrnic of NSSL looked at what it means and what is the impact on receiver-signal processor calibration. Large instantaneous dynamic ranges of more than 80 dB are now possible and Sigmet reported 110+ dB dynamic range digital receivers are already being shipped. Because high speed sampling and processing capabilities, calibrations should be carried into the noise and saturation regions of the receiver.

Alexander Manz of Gematronix reviewed radome loss factor. Computations of the the scattering and the beamwidth effects of the joints were made. He did not recommend modification of the radar constant to account for those small losses. However, radome loss factors due to water on the surface are significant and are being studied.

External Calibration

One of the recurring themes throughout the workshop was the use of the Sun for both alignment and for antenna gain measurements. Ken Tapping of the Dominion Radio Astrophysical Observatory of Canada, a domain expert in the measurement of solar flux, presented a discussion on the use of the Sun for antenna gain and pointing accuracy calibrations. While the measurements are made at 10.7 cm, he showed how the data could be used at other wavelengths. He discussed how the narrow beam weather radars ($<4^o$) should scan the Sun to capture all of the solar flux. In terms of pointing accuracy, at an extreme, solar flares can cause the maximum signal to be displaced to the edge of the solar disk.

Ron Rinehart of UND reviewed his extensive experience with a variety of techniques to successfully measure the gain and the antenna pattern. These include the use of horns, standard targets such as spheres, nodding dihedral reflectors and targets of opportunity. He promoted the search and cultivation of a favourite ground target and demonstrated how it could be used for antenna pattern measurements.

John Lutz of NCAR discussed how the Sun is used to measure the main beam of SPOL for polarisation measurements which are much easier to do than using a ground base CW source. He also showed how they vertically point the radar to fine-tune the Z_{DR} offset.

Dave Brunkow of CSU discussed how they recently performed a successful sphere calibration. The subtitle of his talk was "Most Hated Experiment in Radar Meteorology?" which probably reflected the general attitude on using spheres for calibration. Many have tried and many have failed. He showed how they attached the sphere to a balloon and let it free float. They tracked and searched for a maximum in their data. He concluded that the "most hated" status was undeserved.

As part of the evaluation of future polarimetric upgrades to the WSR-88D antenna, Dick Doviak presented the first "in-field" antenna measurements at NSSL. They essentially set up an antenna test range with a horn and CW source on a 13-storey building. Results matched those made at the factory. They noted some feedhorn spill creating 20 dB side lobes.

Advanced Techniques

John Hubbert of CSU explained how they calibrate the CSU-CHILL polarisation radar using the Sun, test pulses and power measurements. Because of the number of parameters, polarisation systems can be "self-calibrating". They have seen patterns in their Z_{DR} measurements attributable to back side lobes.

Joathrim Vivekanadan of NCAR showed how polarisation radar can be a self-consistent calibrated system by using Z and Z_{DR} to compute K_{dp} since K_{dp} is linearly related to Z/Z_h. They integrate the estimated K_{dp} along a ray and compared to the measured ray integrated K_{dp} to determine the reflectivity bias.

Wind profilers in the demonstration network are not routinely calibrated for power. During the research and development phase, research profilers were calibrated in order to investigate the climatological and geographical distribution of the refractive index structure constant, C_n^2, in order to determine the feasibility of a UHF/VHF approach to profiling the wind. However, Dick Strauch of Colorado University, showed research applications where calibrated systems could be of benefit to ground base radars both in terms of complementary vertical profile measurements but also in terms of system cross-validations.

The Eldora radar is a complex radar system using multiple frequencies and operating on a aircraft platform. Craig Walther of NCAR traced through their calibration procedures. They compute all their losses and then scale the I, Q data accordingly so that the output of the pulse pair signal processor is calibrated. On the aircraft, the peak power varies considerably with temperature and they monitor it to correct their power measurements. Another difference with ground based systems is how and where they take their noise sample since it is not always at far ranges.

Bob Meneghini of NASA reported that the TRMM Precipitation Radar was stable with 0.5 dB using a pre-launch gain-loss versus temperature relationships. As part of the system calibration, a fixed ground based Active Radar Calibrator was available. However, it was not used all that often. The long-term statistics of the surface return is used to assess the stability of the radar. Built into the TRMM data processing is an attenuation correction. Results indicate that the attenuation correction may be overestimated. However there is good agreement in reflectivity at high altitudes. With such stability, there is a possibility of using the TRMM radar data as a common and consistent calibration/validation source for ground radars.

Where there is attenuation, there is emission. Invoking Kirchoff's Law, Fred Fabry of McGill University described how the radar in radiometric (receive) mode could be used to monitor the receiver calibration. As the radar elevation angle decreases, the beam penetrates more atmosphere and therefore the "noise level" of the radar increases, as there is greater gaseous atmospheric attenuation and hence microwave emission. Since the emission can be theoretically computed, the radar measurements can be used to monitor receiver drift.

Validation

Douglas van de Kamp of FSL presented an overview of the extensive efforts to validate the operations of the wind profiler demonstration network. Increasingly, we are seeing efforts to centralise fault and performance monitoring of the radar networks in order to diagnose and prognose problems. This is made possible by network telecommunication capabilities. Built-in test equipment with reporting capability is becoming the standard.

Andy White of the Radar Operations Center described their efforts to calibrate-validate the WSR-88D address both the reflectivity and radial velocity. They clearly state that calibration and validation as inseparable issues and *this includes the radar data processing and product algorithms*. This is a definitive shift in the traditional view of calibration and is very much end-user focussed. The engineering improvements were discussed earlier and have resulted in improvement in the gauge success criteria comparisons. The ROC uses a radical qualitative approach to validate the radar algorithms performances including storm damage reports. It goes much beyond just validating the radial wind speeds.

The issues in the use of radar networks have been addressed in Europe through the COST initiatives for some time and now through GEWEX initiatives. Daniel Michelson of SMHI presented a quantitative approach and analysis on how to use the disparate BALTEX radars in a cohesive fashion through the use of surface rain gauges. The requirement for valid comparisons were a minimum of 3 month integration periods and of the order of 100 rain gauges per radar. Curves of the 10*log(G/R) as function of range for each radar are produced and this is used to normalise or adjust the data for each radar in order to produced rain estimates.

Driven by the discrepancy between the NORDRAD radars, Asko Huuskonen of FMI described their calibration efforts. One of the prime messages is that without an external check it is extremely difficult to sort out systemic errors. Feed horn, sphere, sun and radar overlap statistical studies were conducted with varying degrees of efficacy. Interestingly, in Finland, the sphere calibrations could only be done in winter to overcome the effect of insects. Long integration of the difference of overlapping data between two radars and accumulations provid a very effective tools to monitor the network.

Larry Alford of EEC addressed the issue of demonstrating the phase noise or ground clutter rejection performance of a radar. A demonstration using real ground targets is problematic since the targets, such as mountains or towers, can sway in the wind. They proposed using a crystal delay line approach to validate the phase noise performance.

Isztar Zawadzki of McGill examined the role of drop size distributions variability in calibration and stated that it is the main discrepancy in radar-raingauge daily relations when near the radar, low to the ground and without brightband. He demonstrated that the use of a daily ZR relationship from an optimally sited disdrometer would reduce the standard deviation in the fractional error from 34% to 7.5%.

The merging of radar and rain gauge data is basic to the validation and use of radar for precipitation measurements. Remko Uijlenhoet of Princeton described the care required to do the comparison. Their research experiments have shown that the tipping bucket raingauges are extremely prone to problems and that these problems can be expected in operational systems. The resolutions of these problems are crucial in removing the bias in radar precipitation estimates. They promoted implementations of redundant clusters of raingauges rather than evenly distributed sites.

During the discussion period, David Atlas reminded us of some of the techniques that he had tried from using Bee Bees's, metallic Ping-Pong balls, to disdrometers and to ground based cloud radars. Witold Krajewski of U. Iowa brought out the issue of the spatial correlation of rainfall measurements and the impact on the radar-raingauge comparison problem.

Summary

It was clear that calibration means different things to different people. It is much more just measuring the receiver transfer function. Much of what we mean by calibration now is to make measurements to be able to interpret and to believe the results. Detailed measurements of the radar system characteristics are needed to do this. This definition extension from power to reflectivity to rainfall measurements as the success criteria now brings in the radar equation, attenuation corrections - gas and rain, wet radomes and even vertical profile corrections. It brings in meteorological, physics and algorithm issues such as climatology, the ZR relationship and adjustment algorithms. This later point can be made about velocity algorithm calibration or validation. The term calibration has both a generic and specific usage. This leads to two more specific definitions (proposed):

> ***Validation*** *is a comparison of radar or radar derived quantities with another independent source.*
> ***Adjustment*** *is a modification of the radar quantity to 'match' an external quantity. The modification is application dependent (time and space issues abound here).*

Inter-radar network comparisons (including space borne) have contributed to the way in which the perception of 'calibration' has changed. Consistency checks, in reflectivity or rainrates, have pinpointed procedural or systemic problems in individual or intra-radar networks.

Several presentations reported on the successful use of external targets - spheres, feed horns and ground targets - to measure the gain but also the antenna beam pattern. However, sphere measurements are still hard to make requiring good ground clutter and meteorological conditions and requires substantial data analysis that may preclude their routine operational use.

The use of the Sun for pointing accuracy calibration is now common practice. It is now also used for gain measurements and is integral to the new WSR-88D calibration procedures.

Critical to many procedures is the use of surface raingauge or disdrometers. For single ZR or climatological applications, 3 or more months of data integration are required for adequate comparison. While commonly used, radar-raingauge analysis is still fraught with controversy and pitfalls, deserving a workshop of its own.