NOAA/NSSL's WSR-88D Radar for Research and Enhancement of Operations:

Polarimetric Upgrades to Improve Rainfall Measurements

National Severe Storms Laboratory Report

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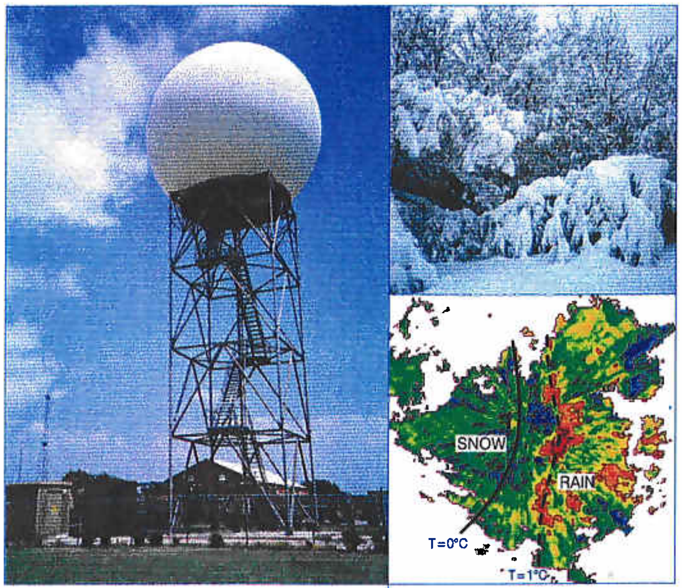
with contributions from: J. Carter, A. Ryzhkov, S. Torres, and A. Zahrai



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National Oceanic and Atmospheric Administration
National Severe Storms Laboratory
Norman, Oklahoma 73069

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RESEARCH and ENHANCEMENT OF OPERATIONS:

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PREFACE

The National Severe Storms Laboratory (NSSL) is the leading NOAA agency for advancing weather radar research, engineering, and applications. Prominent among the high impact projects and experiments conducted at the NSSL was the Joint Doppler Operational Project (JDOP) which gave impetus to the design and establishment of the NEXRAD (now the WSR-88D). To a large part, the WSR-88D is based on the experience with the research Doppler radars developed by NSSL staff. The media for informing the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) management and staff about hardware advances in radar techniques are NSSL reports specifically tailored to the weather agencies' needs. Following extensive research in the mid eighties, two reports dealing with dual polarization capabilities for the NEXRAD were generated for the NWS. (These report titles are listed on the last page of this report.) Since then, more research has been done, and new experiences have emerged. In this spirit, the present report is a successor to those previous reports. It is meant to document the details that lead us to favor a novel scheme for obtaining polarimetric variables in order to improve the quantitative estimation of precipitation. Furthermore, it describes hardware changes in the microwave and antenna assemblies, as well as measurements of the antenna patterns before and after the modifications to the research WSR-88D (designated KOUN1). The report is written for engineers and managers, and the information it contains is detailed enough to gauge the basis upon which recommendations are made for upgrades to the network of WSR-88Ds. This report describes the effects that changes in antenna hardware for polarimetric upgrades have on the radiation patterns, and provides information necessary for making decisions on the selection of a polarization basis. Possible configurations of hardware are also suggested. Ultimately, it is the cost effectiveness (not addressed in this report) that should prevail in the decision process.

EXECUTIVE SUMMARY

This report focuses on the steps undertaken by the National Severe Storms Laboratory (NSSL) to improve rainfall measurements by adding a polarimetric capability to the research WSR-88D (designated as KOUN1). One of the most important elements in obtaining a good polarimetric radar is a good antenna with low sidelobes and matched radiation patterns (i.e., the distribution of radiated power density vs. angular displacement from the beam axis) for horizontally and vertically polarized waves. The polarimetric characteristics and radiation patterns of the KOUN1 radar are presented in Section II. An engineering evaluation was made to determine if the existing antenna assembly with minimum modification could be used for the dual polarization mode. This is indeed the case; therefore, obvious savings in hardware and manpower would ensue by adopting the proposed design.

Because no pattern measurements were ever made of any WSR-88D antennas on site, it was imperative to make measurements on the KOUN1 antenna before the feed was changed from one which transmits only horizontally polarized waves to one (a dual port feed) which transmits both horizontally and vertically polarized waves. The patterns, before change of feed, demonstrate that there are no significant changes in the quality of the antenna installed in 1988.

A dual port antenna feed was purchased from Andrew Canada, Inc. (manufacturers of the WSR-88D antennas) and installed on the radar. Pattern measurements were made for the horizontal and vertical polarizations. It is comforting to note that the radiation patterns with the dual port feed are very close to those patterns measured with the single port feed. For polarimetric measurements, it is desirable to have a good match of main lobes at horizontal (H) and vertical (V) polarizations. Both copolar patterns have low sidelobe levels and are well matched in the mainlobe. Beamwidths are 0.93° for the horizontal copolar and 0.90° for the vertical copolar patterns. The match of patterns in the lower half of the vertical plane is excellent; it even extends to several of the sidelobes. For the most part, the patterns agree within ±1 dB, and the match is best where the gain is largest (i.e., near the beam axis). For the points far removed from the axis, the differences are larger as expected, but because the antenna gain is much smaller in these regions, the differences are much less significant than for those close to the axis.

Cross polarization patterns were also recorded, and it was observed that the WSR-88D specification of < -30 dB is met. The cross-polar pattern at vertical polarization matches in shape the cross-polar pattern at horizontal polarization, but the amplitudes are about 4 dB higher (still within the measurement uncertainty). Consequently, the addition of the dual port feed and the retention of the three struts had not degraded the patterns. Therefore, this configuration is recommended for future polarimetric upgrades of the WSR-88D.

Of critical importance to the favorable utility of a polarimetric radar is the selection of an appropriate polarization basis and its practical implementation. Considerations for the choice of polarimetric basis and a few system design options are described in Section III. The circular and

linear polarimetric bases are compared. It is demonstrated that the circular basis can, in principle, provide estimates of specific differential phase (K_{DP}) without switching the transmitted polarization. In weak showers, these estimates are corrupted because the cross-polar signal is almost three orders of magnitude below the copolar signal. But with circular polarization, the cross-polar signal does not depend on the orientation of hydrometeors; furthermore, in combination with the copolar signal, it leads to the measurement of the mean canting angle. Nonetheless, this apparent advantage of the circular polarization basis vanishes in the presence of significant precipitation along the radar beam. A linear polarization basis is well suited for quantitative measurement of rainfall and classification of hydrometeor types without extensive correction of propagation effects. Therefore, our choice rests with the linear H, V basis.

A novel polarimetric scheme employing simultaneous transmission of horizontally and vertically polarized waves is being implemented on the KOUN1 radar. Principally, the motivation for simultaneous transmission is to do away with an expensive high power microwave switch which has been the key component in research polarimetric radars during the 1980s and 1990s. This design includes installation of two receivers that share several common components, but a single receiver can also measure all the polarimetric variables. With two receivers, the dwell time for computing polarimetric variables is reduced, the ground clutter filter is not affected, and maintenance is simpler. On the down side, the depolarization ratio cannot be measured simultaneously with other polarimetric variables, but if desired, it can be measured together with the standard spectral moments in separate volume scans. Having two receivers offers some redundancy that might be advantageous. For comparative testing, NSSL plans to incorporate two receivers in its radar and still provide full WSR-88D compatibility. That is, all current data acquisition modes and scanning strategies can remain as they are, and the impact of polarimetric implementation on the existing algorithms and products should be minimal.

Theoretical evaluation of the effects that feed alignment, drop canting, and backscatter depolarization have on the measurements of polarimetric parameters is made in Section IV for simultaneous transmission and reception of H and V signals. The simultaneous transmission and reception mode is not detrimental to measurements of the specific differential phase and coefficient of correlation between H, V weather echoes. The effects, however, on differential reflectivity of drop canting along propagation paths can be significant. But these effects are harmful only when differential attenuation dominates, which is a problem whether H, V signals are transmitted simultaneously or alternately. Differential reflectivity and the correlation coefficient could be affected by depolarization due to backscattering from hail mixed with rain. On the other hand, backscatter depolarization would accentuate the hail signature of low Z_{DR} and low ρ_{hv} (i.e., reduce even more the low values of Z_{DR} and ρ_{hv} in hail regions). Thus, the effect might be beneficial.

In summary, the report has demonstrated the following. After the change of feed and one strut on the antenna assembly, the radiation pattern satisfies original WSR-88D specifications. The patterns for horizontal and vertical polarizations are well matched, and the cross-polar pattern is sufficiently suppressed. A linear horizontal and vertical polarization basis is preferred

to a circular basis. The proposed simultaneous transmission and reception of H, V waves is completely compatible with the existing signal processing algorithms on the operational WSR-88Ds. Theoretical analyses of the factors that might affect the precision in measurement of intrinsic polarimetric variables suggests that the simultaneous transmission of H, V waves is a sound method and should be tested.

ACKNOWLEDGEMENTS

We are grateful to the management and staff of the National Severe Storms Laboratory (NSSL), who provided continued support and encourgement to the Doppler radar project during the formative stages in the development of the National Oceanic and Atmospheric Administration (NOAA)/NSSL's research WSR-88D (i.e., the KOUN1). We thank the National Weather Service (NWS) for providing radar parts that made it possible for the NWS Operational Support Facility (OSF) and NSSL to assemble an updated WSR-88D (i.e., the KCRI) on the campus of the University of Oklahoma's (OU) Research Park. This allowed for the transfer of the prototype WSR-88D (i.e., the KOUN1) to NSSL and provided the OSF with a WSR-88D identical to the operational WSR-88Ds they are responsible to maintain and upgrade. OU's Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) management and staff are thanked for providing personnel to this project. Part of the work described herein was supported by Dr. James Rasmussen, Director of the NOAA's Environmental Research Laboratory, with contributions from his Director's Discretionary Fund.

The staff of the NWS Operational Support Facility (OSF) in Norman, Oklahoma, gave us much needed technical guidance concerning the operation of the KOUN1 and provided critical documentation and materials necessary to implement a polarimetric upgrade which this report addresses. Richard Wahkinney and Mike Schmidt of the NSSL provided crucial technical assistance in the design, fabrication, and installation of the components necessary for the polarimetric upgrades. Dale Sirmans of the Titan Corp. was a source of technical expertise concerning WSR-88D details. Dr. John Fagan of the Electrical Engineering Department of OU supplied the GPS system to determine the locations of test equipment used for antenna pattern measurements on the KOUN1. The Physics Department of OU provided a much needed precision rotator to measure the alignment of the polarization ellipse. Dr. Bringi and Mr. Brunkow of Colorado State University provided the data for Figs. IV.12 and IV.13 from the first experimental comparisons of polarimetric data based on simultaneous and alternate transmissions of H,V polarized waves. Joan O'Bannon drafted several figures and composed the cover.

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I. INTRODUCTION

The WSR-88D (NEXRAD) radar system is a national network of weather surveillance Doppler radars serving the National Weather Service (NWS), the Air Weather Service (AWS), and the Federal Aviation Administration (FAA). Operational experience with these meteorological radars has encouraged users' demand for additional capabilities and improvements. Thus, many parallel efforts are underway to resolve deficiencies and implement new features and enhancements. One deficiency is the constraint on developing improved algorithms for product generation (e.g., rainfall accumulation, range-velocity ambiguity mitigation, etc.) caused by specialized computer hardware designed during the late 1970s and early 1980s. Likewise, the Radar Data Acquisition (RDA) unit of the WSR-88D is based on a custom signal processor and other subsystem components whose proprietary nature makes systematic replacement and incremental upgrades extremely difficult. Thus, the NSSL has been tasked to develop a Radar Product Generator (RPG) and an RDA unit using an open system design which incorporates off-the-shelf components meeting rigid standards.

One of the enhancements to the WSR-88D, to be made possible by upgrading the RDA to an open system design, is the addition of a polarimetric capability to improve rainfall estimation and to make possible the identification of precipitation types (e.g., distinguishing rain from hail, snow, etc.). Relations between radar reflectivity factor Z and rainfall rate R have been used for several decades to estimate rainfall accumulation, forecast flash flood conditions, etc. Although high reflectivity factor values correlate with high rainfall rates, there is no unique relation between the two. To improve the accuracy of the rainfall estimated with radar, considerable effort has been expended by meteorologists over the past decades to develop techniques to tune the R,Z relations to specific types of rain (e.g., stratiform, convective, etc.). Also, the WSR-88D radar, which presently measures Z for horizontally polarized waves, has not changed the basic way in which rainfall is measured. Improvements in rainfall estimation brought about by the WSR-88D are due to improvements in radar calibration, narrow beamwidth and lower sidelobes, real-time access to rain gauges to tune the R,Z relations,etc. Fundamentally, there has not been any significant change in the way rainfall is estimated by the WSR-88D.

This state of affairs has been dramatically altered by research initiated in the late 1960s at the National Research Council, Ottawa, Canada, (Barge 1970; 1974), and at the Ohio State University in the early 1970s (Seliga and Bringi 1976) which showed that the added information provided by a polarimetric radar has the potential to detect hail and improve the accuracy of estimating rainfall. The focus of the later research was to use polarimetric information (i.e., differential reflectivity factor Z_{DR} measured using both horizontally and vertically polarized waves, in addition to Z) to estimate the parameters of an assumed two parameter drop size distribution. Rainfall rate based upon Z measured with a single linearly polarized wave constrains the assumed drop size distribution to a single parameter; in general, the drop size distribution can only be accurately described by a distribution function having many parameters. Remote measurements with polarimetric radars are based on the assumption that the eccentricity of drops increases predictably with their size (Beard et al. 1989). The Z_{DR}, Z approach to improve rainfall estimate assumes that rain rates measured with singly polarized waves (e.g., like that transmitted by the WSR-88D) have errors principally caused by highly variable drop size distributions; these cannot be measured with a single, linearly polarized wave. On the other hand, Zawadski (1984) pointed out that variability of drop-size distributions is only one of many factors that affect the accuracy with which radar measures rain, and it is not necessarily the most important factor.

Sachidanada and Zrnic (1986) showed that the relation between specific differential phase (i.e., the differential propagation phase shift per unit length between vertically and horizontally polarized waves) and rainrate is relatively insensitive to drop size distribution and, thus, can also form the basis of rain measurement using a single parameter relation (i.e., an R,K_{DP} relation). Equally important, Zrnic and Ryzhkov (1996) have shown that the specific differential phase method of measuring moderate to heavy rain rates overcomes many of the factors that limit rain measurement accuracy (e.g., calibration errors, wet radome, ground clutter backscattered routinely or through anomalous propagation conditions, underestimation of extreme rainfalls, attenuation, ground clutter canceller bias, etc.). Thus, the addition of a polarimetric capability to the WSR-88D will provide, for the first time, a revolutionary approach to the radar measurement of rainfall. This improvement could significantly increase the accuracy of rainfall measurements, lead to issuance of more timely and accurate flash flood warnings, and provide other improved hydrological products of importance to agricultural and commercial enterprises.

Recent experiments with dual-polarized Doppler weather radars have demonstrated great potential in solving a variety of problems in operational meteorology. The following is a list of what dual polarization can do:

- Improve quantitative precipitation estimation
- Discriminate hail from rain, possibly gauge hail size
- Identify precipitation type in winter storms
- Measure precipitation in the presence of ground clutter
- Identify electrically active storms
- Identify the presence of insects, birds, and chaff
- Improve the accuracy of VAD winds
- Provide initial conditions and constraints to numerical models
- Identify aircraft icing conditions

This report focuses on the steps undertaken by the National Severe Storms Laboratory (NSSL) to improve rainfall measurements by adding a polarimetric capability to the research WSR-88D (designated as KOUN1). One of the most important elements in obtaining a good polarimetric radar is a good antenna with low sidelobes and matched radiation patterns (i.e., the distribution of radiated power density vs. angular displacement from the beam axis) for horizontally and vertically polarized waves. The polarimetric characteristics and radiation patterns of the KOUN1radar are presented in Section II. Section III contains a critical comparison of two polarimetric bases (linear and circular) to decide which basis to implement. Section III also reviews the options of simultaneously transmitting horizontally (H) and vertically (V) polarized waves or implementing the well-tested option of alternately transmitting H and V waves. Principally, the motivation for simultaneous transmission is to do away with an expensive high power microwave switch which has been the key component in research polarimetric radars during the 1980s and 1990s. Furthermore, simultaneous transmission and reception is completely compatabile with the existing signal processing algorithms and procedures that have been implemented and tested on the national network of operational WSR-88D radars over several years. Section IV provides a theoretical analysis of the factors that might affect the precision in measurement of intrinsic polarimetric variables if simultaneous transmission of H, V waves is used.

II. PATTERN MEASUREMENTS OF THE RADIATION FIELDS FROM NSSL'S RESEARCH WSR-88D RADAR

One of the modifications being made to NSSL's WSR-88D radar is conversion from one that transmits and receives only a horizontally polarized electric field to one in which both vertically and horizontally polarized fields are transmitted and received, simultaneously, in two receiving channels. This will allow polarimetric variables (e.g., the differential phase and the correlation between horizontally and vertically polarized echoes) to be measured directly. Polarimetric variables are important to the potential improvement of rainfall rate measurements with the WSR-88D radar network.

The WSR-88D antenna has a reflector with a diameter of 8.53 m (28 feet) illuminated by a primary radiator supported by three spars (Fig. II.1a). The focal length to diameter ratio f/D of the reflector is 0.375. The frequency assigned to operate this radar is 2705 MHz, corresponding to a wavelength of 0.111 m.

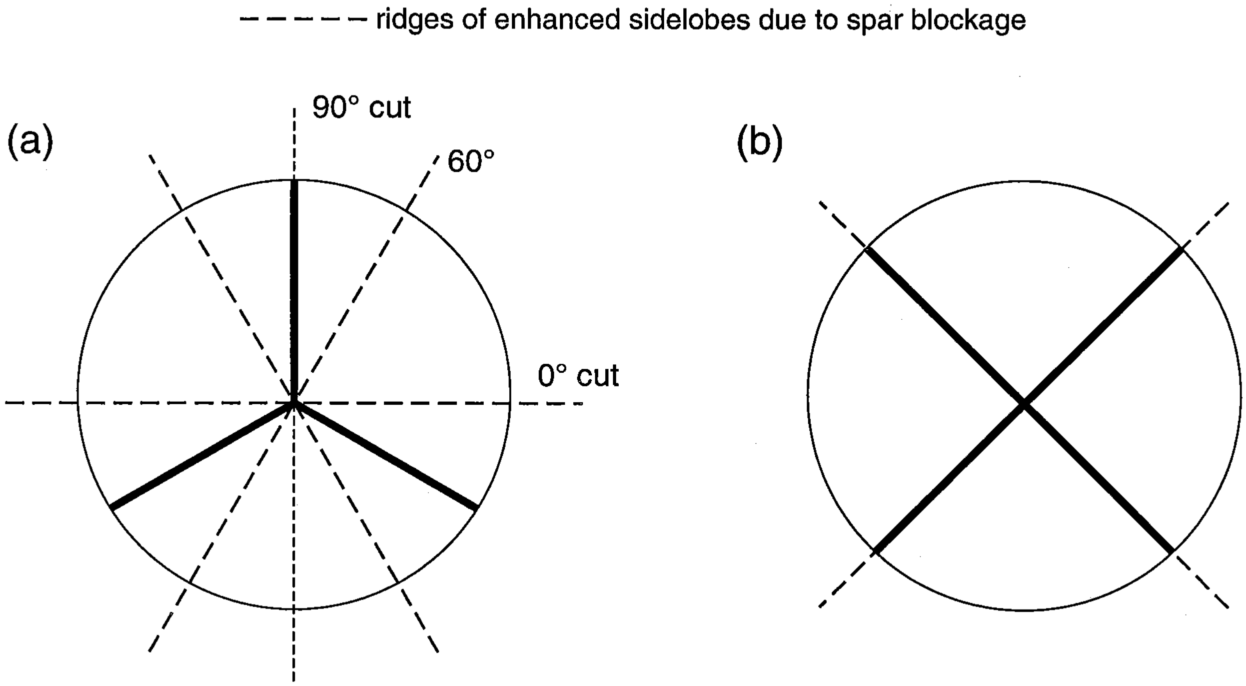
II.1. Radiation pattern measurements of NSSL's research WSR-88D (the KOUN1 radar) before the change to a dual port feed.

No pattern measurements were made on the KOUN1 radar installed near the NSSL in 1989, nor, for that matter, were antenna measurements made after any of the WSR-88D antennas were installed at their respective sites (with or without radomes). Therefore, it was imperative to make measurements on the existing antenna before the primary radiator was changed from one which transmitted and detected radiation having only horizontal polarization (i.e., the electric field is horizontal) to one that transmits and detects fields having both horizontal and vertical polarizations. These measurements would serve as a baseline to compare radiation patterns obtained with the new primary radiator or feed which illuminates the paraboloidal reflector of the KOUN1 radar, as well as to determine if there were any significant changes from the radiation patterns measured at the manufacturer's (Andrew Canada, Inc.) antenna range.

II.1.1 Pattern measurements made at the manufacturer's antenna range

Radiation pattern measurements were made on several WSR-88D antennas, usually without radomes, using the antenna range of Andrew Canada. At this facility, the WSR-88D antenna is rotated azimuthally about a vertical axis, while the axis of the paraboloidal reflector remains in a horizontal plane. Although all pattern measurements are made by rotating the antenna about a vertical axis while the beam is pointed at the horizon, the paraboloidal reflector can be rotated about its axis so that pattern measurements can be made along various planes (or "cuts") through the beam (i.e., the main lobe) center.

For example, the 0° cut gives a pattern measurement as a function of the azimuthal angle for the antenna in its normal configuration (i.e., as in Fig. II.1a); for the 90° cut, the reflector is



WSR-88D ANTENNA
3 spars

CSU AND NCAR ANTENNA
4 spars

Fig. II.1 (a) Feed support configuration on the WSR-88D antenna. (b) the four-spar configuration used on antennas at the Colorado State University (CSU), and at the National Center for Atmospheric Research (NCAR).

rotated 90° about its axis, and the antenna is again rotated about the vertical to simulate a pattern measurement in the vertical plane. A sample of the one-way radiation patterns, measured on Andrew Canada's range for linear horizontally polarized waves at a frequency of 2700 MHz, is given in Figs.II.2a, b (reproduced from the Paramax Systems Corp. report, 1992). *These patterns were measured without a radome* and are the copolar patterns in the plane of the electric field (i.e., in the E-plane which is the 0° cut for a horizontally polarized fields).

To highlight the levels of the far-out sidelobes, Fig. II.2a shows the full 360° pattern for radiation below the -40 dB level, whereas Fig. II.2b shows the pattern of sidelobes nearby the main lobe and the radiation pattern of the main lobe itself (the left side on a ±20° scale, and the right side on a ±2° scale; adapted from the Paramax System Corp. report, 1992). The heavy solid lines in Fig. II.2 are the maximum sidelobe levels allowed by the NEXRAD specification number DV1208252G when the antenna is in its radome. Measurements of antenna patterns with and without a partially assembled radome, made by Andrew Canada over a ±20° interval (not presented here) indicate that the radome has negligible effect on the main lobe but alters the sidelobe levels; mostly increasing them. Nevertheless, the increase in sidelobe levels near the

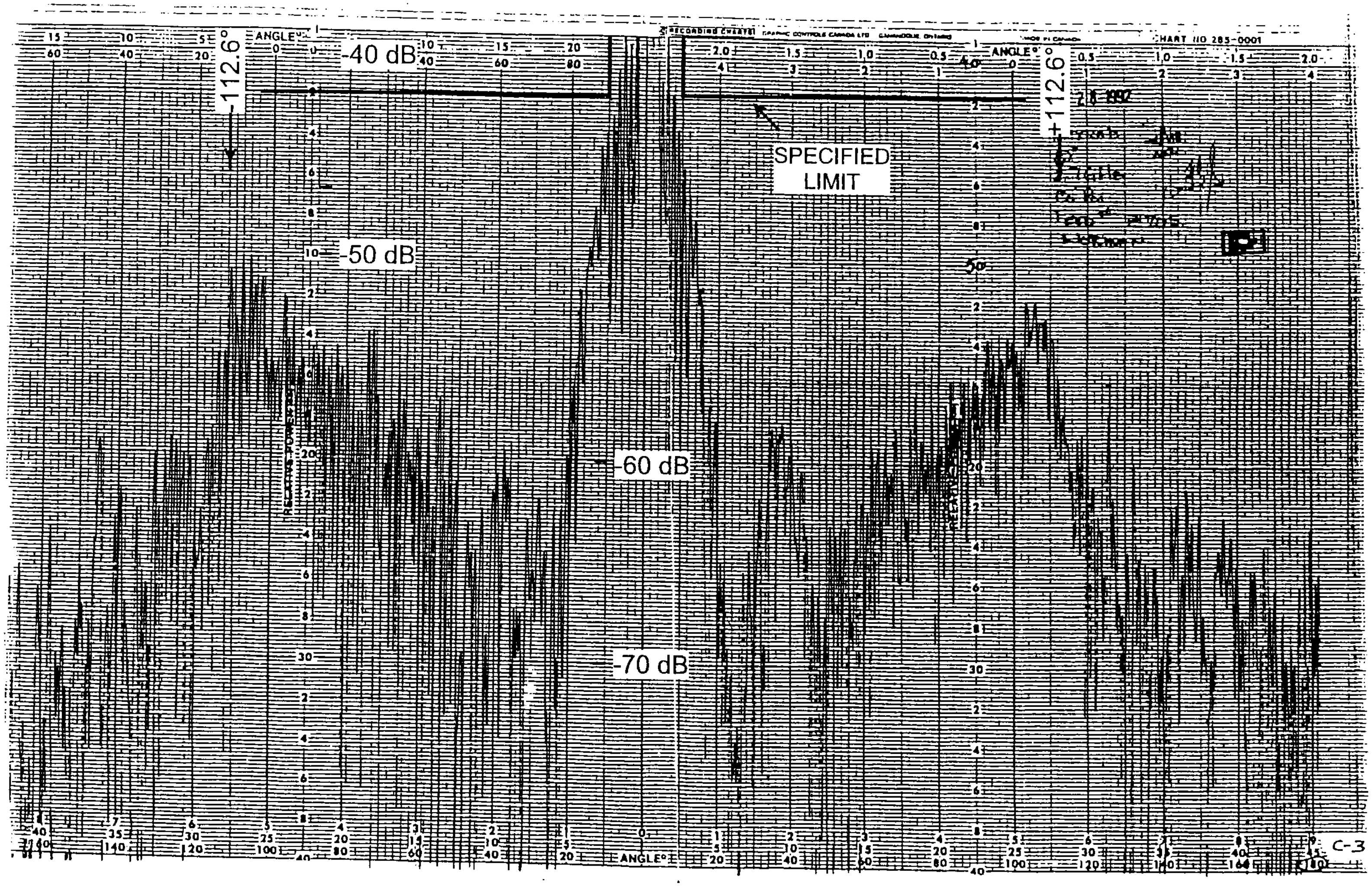


Fig. II.2 The copolar radiation (HH) pattern (0° cut) for horizontally polarized fields radiated by the WSR-88D reflector, without radome, on the antenna range of Andrew Canada Inc. The dB scale is relative to the peak of the main lobe. (a) the radiation pattern over ±180°; only the pattern portion below -40 dB is shown.

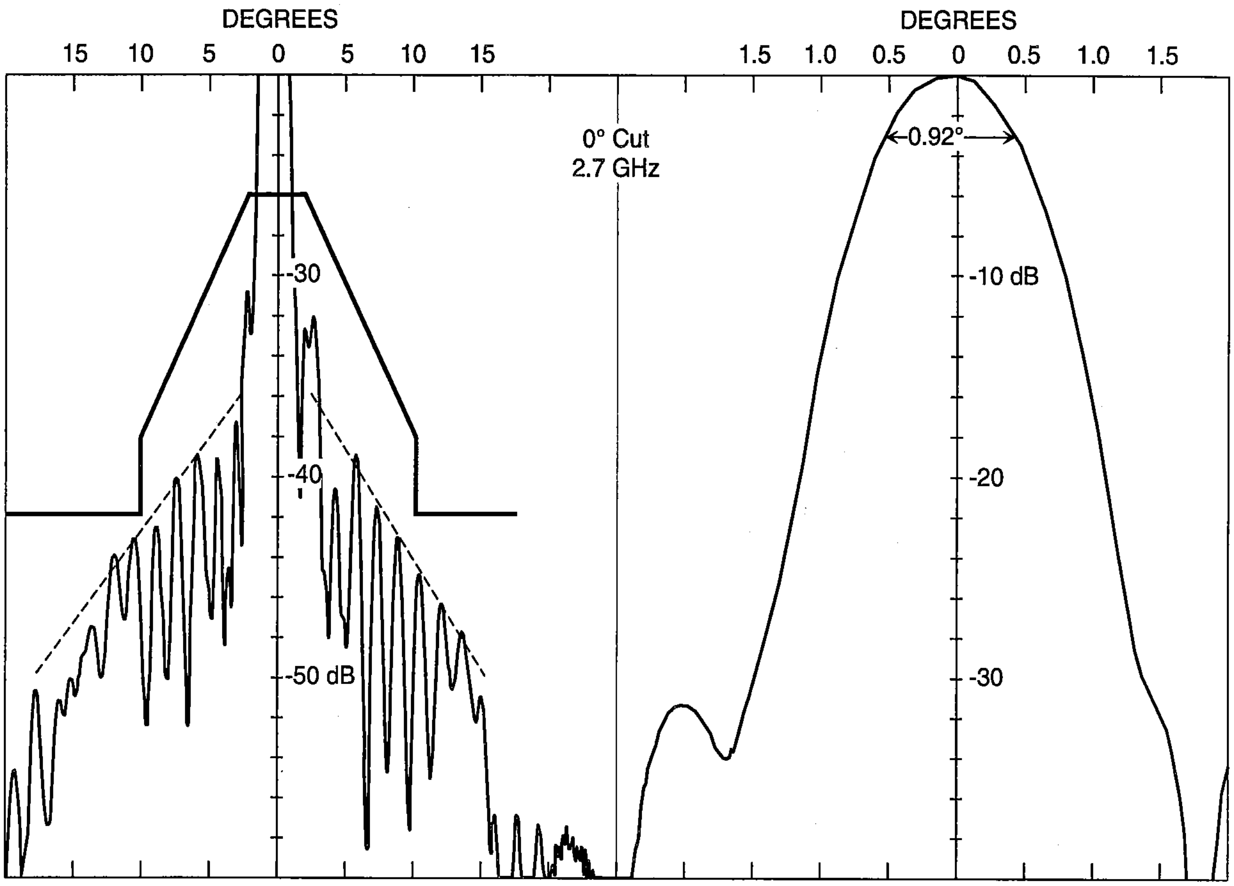


Fig. II.2 (b) left side: the near side lobes shown over an azimuthal interval of about ±20° about the main lobe; heavy solid lines are the specified maximum sidelobe levels with radome. Dashed lines are the approximate envelope of the sidelobes between 3° and about 16°. The figure to the right is the main lobe or beam pattern over an azimuthal interval of about ±2°.

main lobe is no more than 2 dB. These increases did not cause the sidelobe levels to exceed the specified limits.

The sidelobes far removed from the main beam (Fig. II.2a) show a monotonic decrease to about the -65 to -75 dB levels at ±25°, followed by an upward trend to about the -50 dB level at ±110°, beyond which the sidelobes decrease in amplitude. This increase of sidelobe level, to a peak near 110°, is inferred to be radiation transmitted principally from the feed of the WSR-88D antenna. The sudden decrease in sidelobes beyond about 110° occurs because the primary radiation from the feed and scatter from the spars is obscured by the reflector; calculations show that focus of the reflector is obscured at an angle of 112.6°, which supports the inference.