"TERMINAL DOPPLER WEATHER RADAR CLUTTER CONTROL"[1]

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ABSTRACT

The FAA is developing the Terminal Doppler Weather Radar system to automatically detect low altitude wind shear due to microbursts and gust fronts. Detection of this phenomenon presents a significant radar engineering challenge due to the need to observe low reflectivity events in the presence of strong clutter from ground objects and range aliased weather returns. This paper describes a number of unique approaches to clutter rejection which have been validated with the TDWR testbed radar.

I. INTRODUCTION

Low altitude wind shear has been recognized as a major cause of air carrier fatal accidents in the United States. The Federal Aviation Administration has initiated the Terminal Doppler Weather Radar (TDWR) program to develop a reliable, fully automated, wind shear detection system using pulse Doppler radars. The TDWR will detect phenomena, such as microbursts and gust fronts, which cause low altitude wind shear. The detections will be used to generate warnings that will help pilots successfully avoid wind shear on approach to, and departure from, an airport [1]. Fig. 1 depicts the microburst which is the outflow from a small scale down draft generated by a thunderstorm, rain shower, or perhaps a harmless-looking cumulus cloud. The TDWR will typically be located near an airport at which such microbursts are to be detected, and determine the three dimensional structure of the storm by a series of horizontal (PPI) scans near the surface and aloft.

The detection of low altitude wind shear presents a difficult challenge due to the need to detect low reflectivity distributed objects in the high clutter environment near the radar. In this paper, we will focus on key aspects of the detection problem from the viewpoint of a **radar engineer** (as opposed, e.g., to the very interesting meteorological [6,9] and pattern recognition [3,10] features of the problem). Our focus will be on mainlobe clutter suppression, since it is a principal cause of inadequate detection performance. Additionally, we will emphasize unique[2] features developed and validated experimentally with the TDWR testbed radar.

To provide a framework for the TDWR system discussions, we will first describe the salient features of the low altitude wind shear detection environment and the pattern recognition algorithms. We will then discuss some of the system features which arise from ground clutter suppression considerations. Clutter due to out-of-trip weather returns is also an important factor in TDWR system engineering due to the tradeoff between unambiguous velocity and range (coupled with the (range)$^{-2}$ power law for weather echoes). Finally, we will discuss some of the radar engineering areas which warrant additional investigation.

II. WIND SHEAR PHENOMENA FEATURES

The microburst outflows such as illustrated in fig. 1 are particularly challenging to detect due to the low height of the outflow [typically 200-700 m. above ground level (AGL)], short duration (typically 10 minutes) and the low reflectivities associated with the outflow in certain situations [4]. Since the wind velocity is determined from Doppler radar measurements of the motion of volume scatterers, the target return is conventionally characterized by the reflectivity factor $Z = K \lambda^4 \eta$ where λ is the wavelength, K a constant and η the volume reflectivity (in m^2/m^3). Moderate rain has a Z of approximately +35dB with respect to 1 mm^6/m^3 (i.e., +35 dBZ), while clear air reflectivities typically are less than +15 dBZ. Measurements in Denver [4], where the atmospheric conditions, are conducive to evaporation of rain drops beneath the clouds, have shown that an appreciable number of microbursts can have outflow reflectivities between 0dBZ and +10dBZ. Microbursts may be viewed as approximately circular[3] with a diameter of 1-4 km.

Gust fronts, which often arise as the leading edge of a long lasting outflow from a thunderstorm (see fig. 1), typically have low reflectivities even when the parent storm has high reflectivities. This is because the outflow leading edge propagates a considerable distance (as much as 40 km) away from the parent storm.. Gust fronts can have reflectivities comparable to those observed in Denver, CO microbursts, but typically have a greater vertical (1 to 3 km AGL) and a much greater horizontal (width of 1-3 km and a length typically greater than 10 km) extent.

III. RADAR SYSTEM FEATURES

The TDWR is a C-band pulse Doppler radar with a 0.5° beamwidth, sidelobes of -27 dB to - 40 dB, 1 μs pulses, and PRF values consistent with velocity and range ambiguity considerations (to be discussed subsequently)[4]. Weather parameter estimation considerations require a fairly extended dwell time (approximately 40 ms) at each of the (1° in azimuth) radials at which the weather is to be measured, and make mechanically scanned antennas the cost effective solution.

The TDWR is designed to provide at least a 1 minute warning for aircraft before they encounter hazardous wind shear at altitudes below 330 m AGL. This requires coverage out to approximately 6 km from the ends of the airport runways. By siting the radar approximately 15 km from the airport center, it is possible to scan the high priority coverage region with a series of sector PPI scans at the surface (approximately 1 per minute) and aloft (to detect microburst precursors, thus improving the timeliness of the warnings [10]). Additional 360° PPI scans are used for gust front detection [11].

The short life of microbursts makes it essential to have a fully automated, quickly reacting, detection system that does not rely on meteorologists for data interpretation. The pattern recognition algorithms used to detect microbursts (see fig. 2) and gust fronts have sophisticated logic to minimize errors caused by imperfect velocity data; the wind shear events of concern typically have a smooth velocity field [3, 4]. However, missing or erroneous data over a 0.3-.7 km (3-6 range gates) interval might prevent pattern recognition on a given radial. If pattern recognition fails on too many adjacent radials in the shear region (e.g., more than 2-5) an event may be missed. Clutter levels which are comparable to the weather reflectivity may cause the data to be rejected by the algorithm logic, or possibly cause significant errors in the algorithm results.

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[1] This work was sponsored by the Federal Aviation Administration. The United States Government assumes no liability for its contents or use thereof.

[2] i.e., features which are different from conventional air traffic surveillance and/or current operational weather radars.

[3] many microbursts are more elliptical than circular and may even in some cases form lines.

[4] space does not permit describing the tradeoffs which led to many of the radar system parameters. See ref [13] for the rationale behind many of the key parameters. The TDWR testbed radar used for the validation is currently an S-band radar with 1.0 degree beamwidth and 0.65 μs pulses, but will be converted to C-band in 1990.

IV. GROUND CLUTTER SUPPRESSION

Since isolated (i.e., single range gate) high level point clutter is unlikely to create false alarms or cause significant problems in detecting wind shear events, distributed ground clutter has been the main concern for overall system sizing and design. Measurements of the clutter environment have been carried out using a variety of radars at S and X-band to determine representative clutter levels at major airports. Based on these measurements, taken at near grazing incidence, and others described in the literature, we assume an urban area clutter reflectivity (σ^o) of -40 dB for system sizing. It can be shown that this environment requires approximately 54 dB of clutter suppression at 10 km range to achieve the desired +10 dB signal to clutter ratio (SCR) for a 0 dBZ weather target.

A. System Features to Support Ground Clutter Suppression by MTI Filtering

High quality moving target indicator (MTI) high pass linear filters are a principal element in obtaining the requisite clutter suppression. Numerous papers in the literature have described filter designs capable of achieving 50 dB (or greater) clutter suppression against fixed ground targets while taking into account the clutter spectrum spreading due to antenna rotation and wind [5]. However, there are important system hardware requirements which must be met if the desired results are to be obtained. Experience has shown that when these are inadequately considered they become a principal limitation, and thus warrant discussion here.

1. Transmitter-receiver instabilities

Transmitter-receiver instabilities are a key factor in the overall system performance; these instabilities can lead to results that are counterintuitive when MTI filtering is used. Small variations in the received pulse amplitudes and/or phases of the return from a fixed cross section scatterer cause the received signal spectrum to have components which lie in the passband of the MTI filters. Generally, these components are sufficiently weak (e.g., at least 20 dB below the expected target return) that they do not affect measurement accuracy when only weather is present. However, when these components are generated by a large amplitude clutter signal, they may dominate the weather return even if the nominal clutter return is rejected by the MTI filters.

When the instability components are dominated by a single line in the frequency spectrum, the result can be a velocity estimate corresponding to that frequency (e.g., 4.5 m/s for a component at 180 Hz). The velocity estimate in a region of high clutter can, therefore, appear to correspond to a steady wind in that region . If this region of false wind indication lies next to a region of valid wind data of the opposite sign, a false alarm may occur. This can seem very puzzling to users who expect that clutter-dominated returns will create zero velocity estimates. This problem has been addressed in the TDWR context by:

a. designing the radar transmitter and receiver system so that the instabilities are consistent with the desired clutter suppression,

b. monitoring the actual instability levels (e.g.,by analyzing the return from a 3 μs delay line and/or from stationary targets), and

c. real time flagging of measurements which are dominated by clutter residue returns
(as discussed below).

2. Use of "instantaneous" AGC to achieve adequate dynamic range

Another important hardware system factor for achieving the desired clutter suppression performance is adequate dynamic range. The MTI clutter suppression capabilities required for radar-based low altitude wind shear detection generally can be realized only by digital processing of a digitized return. In particular, one must insure that the clutter signal and weather signal both lie within the effective linear aperture of the A/D converter (ADC), so that there will be a weather signal to measure once the clutter signal has been suppressed by the MTI filters. If one wishes to effectively reject clutter which is as much as 40 dB stronger than weather reflectivities in the range -10 dBZ to +60 dBZ, the required linear dynamic range is approximately 105 dB. This is beyond the capability of current commercially available ADC's. The current solution to this problem in the TDWR context is to use a fast acting (i.e., varying pulse by pulse) automatic gain control (AGC) in front of a 12 bit ADC.

Fig. 3 shows the AGC used in the TDWR testbed radar[5]. The 12 bit ADC samples at 1.25 MHz, with an rms noise level of approximately 2 digital levels in low SNR conditions to minimize velocity biases due to quantization noise. When the input SNR is greater than approximately 60 dB, attenuation is inserted to keep the ADC input within the linear range of the ADC. A 6 bit flash-type ADC samples the logarithmic channel at a 15 MHz rate and then sets the AGC for the range gate based on the peak logarithmic value within the gate. A 240 m. coaxial cable delays the main IF signal so that the AGC can switch (in 50 ns) to a setting for the range gate which sets the input some 3 dB below the ADC saturation level. The output of the ADC is corrected by a lookup table of complex coefficient values to restore the I/Q values to their actual dynamic range.

B. Clutter Residue Map Editing

To date, the practical suppression achievable with MTI filters at the elevation angles used for microburst outflow detection has been less than 50 dB. Testing at Huntsville suggested that suppression of approximately 35 dB was achieved in practice[6]. More recent testing in the Kansas City has demonstrated suppression of approximately 45 dB at operational scan speeds. Fig. 4 shows the received signal at the TDWR test location near Denver, CO on 5 July 1988, with the elevation angle adjusted for optimal gust front detection. The elongated north-to-south features about 40 km to the west are clutter residue returns from the Rocky Mountains which could be confused with valid gust front returns. The returns exceeding 30 dBZ to the south of the radar are legitimate thunderstorm returns.

We see from fig. 4 that the MTI filters passed regions of clutter residue which have reflectivities comparable to those of the desired targets. A clutter residue editing map is used to flag these regions on a data adaptive basis. The clutter residue is estimated from "clear air" measurements[7], and the measured data during weather periods is compared to the estimated clutter residue values on a gate by gate basis. If the measurement for a gate during normal weather detection operations does not exceed the clutter residue map level by a site adaptable threshold (X_{cr}), the gate is flagged.

Fig. 5 shows the results of editing the scan data from fig. 4 with an editing map generated on April 4, 1988. The bulk of the clutter returns from the mountains, and some high level point clutter within 20 km range, are rejected, as indicated by the white "invalid" regions in the data. A small thunderstorm over the mountains is now clearly delineated. Nevertheless, some clutter breakthough still exists.

The clutter residue editing map has been assessed by measuring the ability to detect known events as a function of clutter suppression parameters such as the clutter residue map data measurement period and the data flagging threshold. Preliminary results show a marginal improvement in the already good microburst detection near Denver (in part due to the lack of extended clutter near the airport runways), but a major improvement in gust front detection performance (by flagging of clutter from ridges and mountains to the west of the airport). In particular, the use of a

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[5] this scheme was first implemented in a weather radar context in the CHILL radar of the Illinois State Water Survey [12].

[6] the Huntsville suppression results may have been biased downward by difficulties in distinguishing between clear air return and clutter residue, as well as deficiencies in system calibration and dynamic range.

[7] the clear air return reflectivity (Z_{ca}) is estimated from measurements at elevation angles with negligible ground clutter residue. It is not possible, using our procedure, to identify gates with a clutter residue whose reflectivity is $\leq Z_{ca}$.

clutter residue map reduced the gust front algorithm false alarm rate from approximately 45 % (in 1987) to only 2 % (in 1988) without degrading the detection probability.

Clutter residue is a random process which varies temporally about its average value for each range gate. By increasing the threshold parameter X_{cr}, one can reduce the clutter residue "breakthrough" rate at the cost of flagging more valid data. Fixed point target detection systems typically would use a large X_{cr}. However, our experiments suggest that the bulk microburst detection performance is only marginally affected by large changes (e.g., from 5 dB to 10 dB) in X_{cr}.

V. SUPPRESSION OF CLUTTER DUE TO RANGE ALIASING OF DISTANT STORMS

Doppler weather radars operating at constant pulse repetition frequencies (PRF) must cope with the clutter caused by range aliased echoes from distant storms. This problem arises from the standard range-velocity ambiguity relationship[8] coupled with the difficulty in achieving MTI clutter filter suppression of 50 dB with anything other than a constant PRF pulse train.

The TDWR adaptively selects PRF to minimize "distant weather" clutter near the airport. Unambiguous reflectivity measurements of distant storms made at a very low PRF[7] are used to predict the level of clutter for various operational PRF's. A PRF is selected which minimizes the level of clutter in the region of interest.

When out-of-trip weather clutter unavoidably occurs in a region of concern, the TDWR testbed flags the contaminated gates. Using the long range unambiguous measurement, the out-of-trip return in each gate is estimated (for the PRF selected). The estimate for each gate is compared to the actual signal received in the gate; gates whose signal does not exceed the out-of-trip return estimate by a site adaptable threshold are flagged.

The flagging technique and threshold used do not eliminate all contaminated gates, especially when in-trip signals are similar in strength to out-of-trip signals. However, the majority of the contaminated gates, in particular those which are heavily contaminated, are flagged. The remaining out-of-trip contamination does not tend to trigger microburst and gust front pattern matching algorithms, so the probability of false alarm is reduced. Because of the conservative nature of the flagging, overall probability of wind shear detection is unaffected. However, the technique cannot recover wind shear events which are completely obscured by range aliasing.

Figures 6 and 7 compare reflectivity fields before and after out-of-trip editing,[9] for a Kansas City (MO) data set in which the out-of-trip weather caused a false alarm. We see that the editing algorithm eliminates most, but not all, of the data which has been corrupted by the out-of-trip weather. The editing, though not complete, is effective enough that the false alarm no longer occurs. For 3 days of Kansas City data severely corrupted by out-of-trip echoes, 80% of the microburst false alarms due to out-of-trip weather were eliminated by the editing procedure.

VI. SUMMARY

Clutter suppression is a challenging problem for the TDWR, due to the need to observe returns from weak scatterers (in some cases clear air returns) in the presence of strong urban clutter and/or range aliased returns from distant storms. We have discussed several novel radar design features which have enabled the TDWR testbed to provide reliable wind shear detection performance in the challenging environments at Denver, CO and Kansas City, MO. Research is continuing in the following areas:

1. innovative filtering techniques which can provide MTI clutter suppressions of 50 dB, using signal waveforms that minimize range folding while still providing unambiguous velocity estimates,

2. rejection of very strong point targets such as aircraft which create interference in several adjacent range gates due to IF filter "ringing",

3. determination of why the expected ground clutter suppression is not fully achieved in practice,

4. use of phase modulation on the transmitted waveforms to minimize velocity errors when range aliased echoes occur, as well as improved editing techniques for such clutter, and

5. the use of storm structure aloft information [10] to minimize false alarms due to non- stationary clutter residue (such as "anomalous propagation" returns), and the returns from extended moving scatterers (such as bird flocks).

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[8] the product (unambiguous range) (unambiguous velocity) = c l/8, where c is the speed of light and λ is the wavelength.

[9] Figure 7 was obtained by flagging gates whose received power was less than 1.5 dB above the estimated out-of-trip weather return power. This results in less flagging of valid data and a higher acceptance rate of invalid data than the corresponding NEXRAD data quality algorithm.

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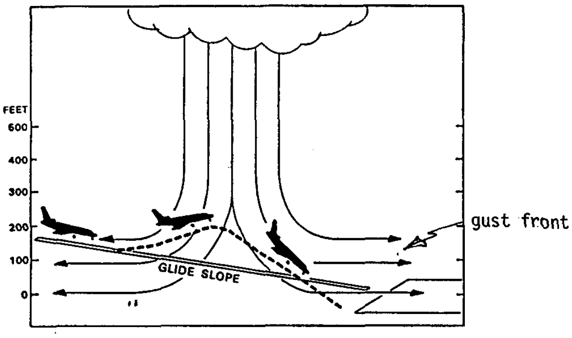
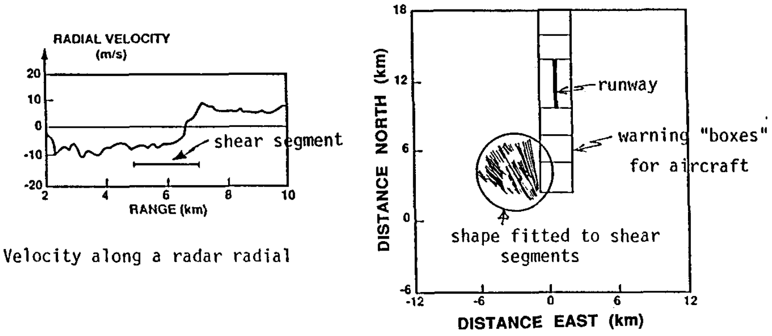


Fig. 1 Aircraft Encounter with a Microburst



Velocity along a radar radial

Fig. 2 Microburst Outflow Detection Algorithm

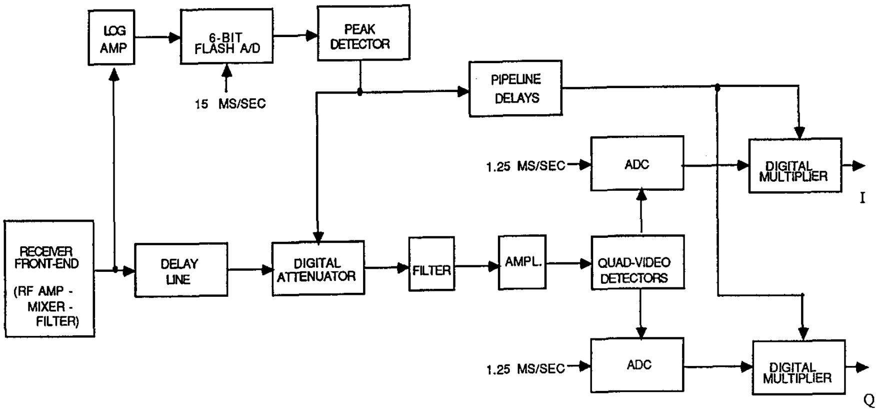


Fig. 3 Block Diagram of TDWR Testbed Radar AGC Processing

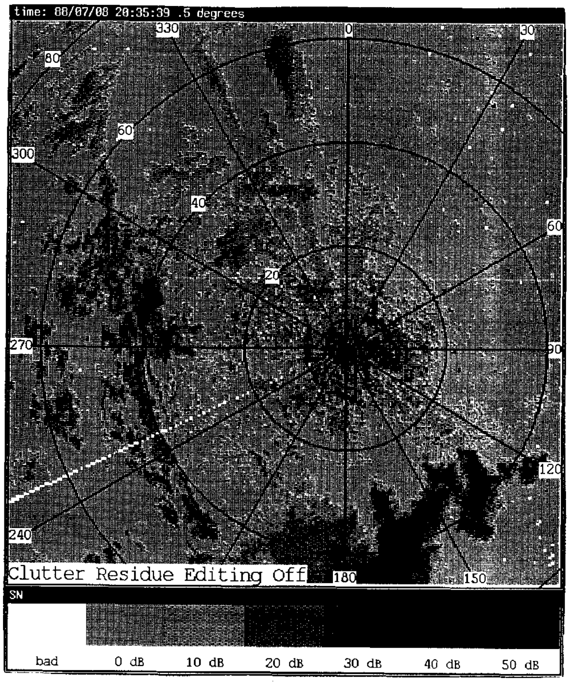


Fig. 4 TDWR Testbed Denver Reflectivity Data with Residue Clutter

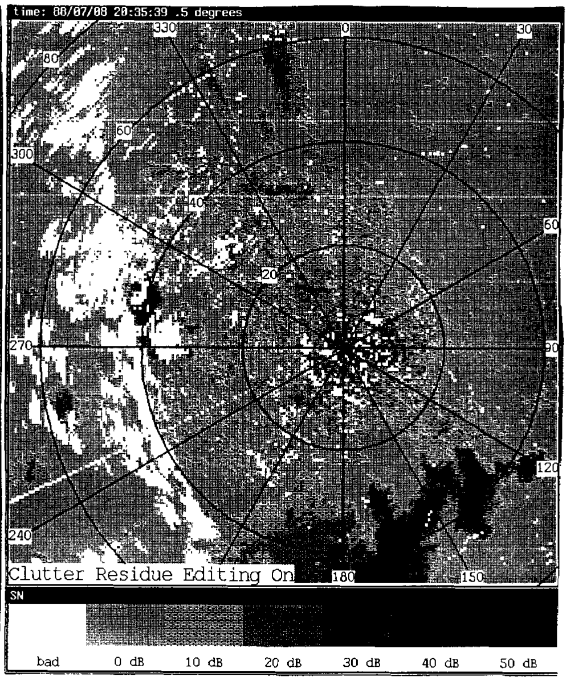


Fig. 5 Reflectivity Data After Clutter Residue Editing

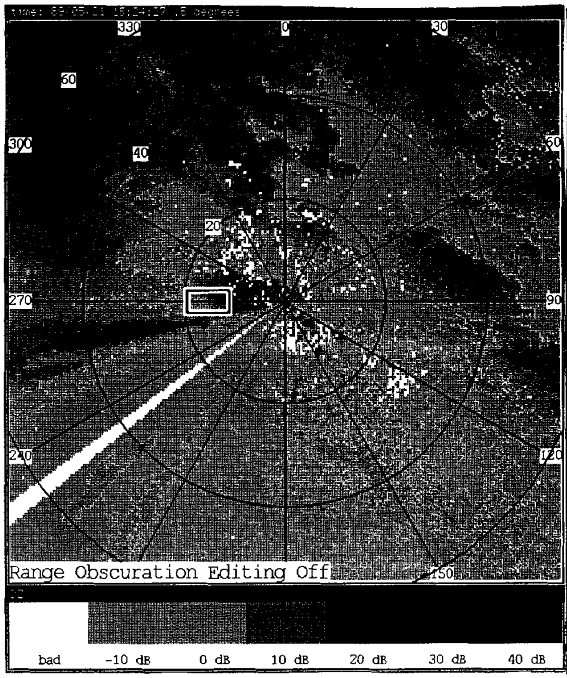


Fig. 6 TDWR Testbed Kansas City Reflectivity Data with Out-of-Trip Contamination. Microburst False Alarm is Indicated by Box.

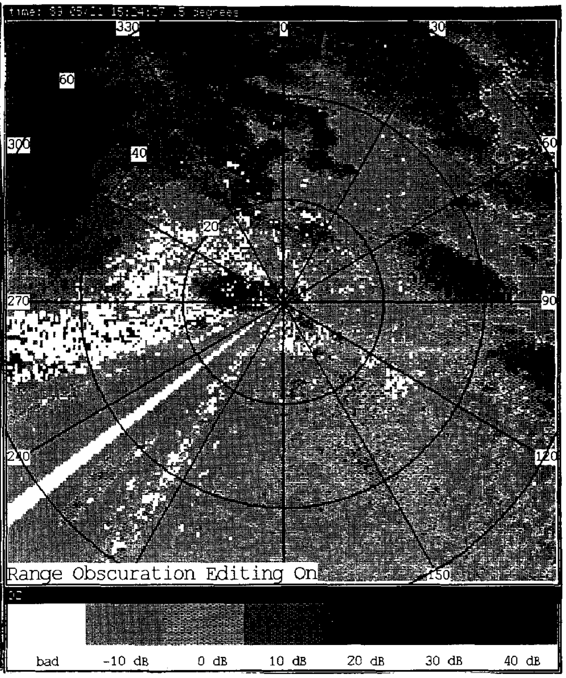


Fig. 7 Reflectivity Data After Range Obscuration Editing