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Attenuation of Weather Radar Signals Due to Wetting of the Radome by Rainwater or Incomplete Filling of the Beam Volume

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ABSTRACT

A search of scientific literature, both printed and electronic, was undertaken to provide quantitative estimates of attenuation effects of rainfall on weather radar radomes. The emphasis was on C-band (5 cm) and S-Band (10 cm) wavelengths. An empirical model was developed to estimate two-way wet radome losses as a function of frequency and rainfall rate for both standard and hydrophobic radomes. The model fits most of the published data within +/- 1dB at both target wavelengths for rain rates from less than ten to more than 200 mm/hr. Rainfall attenuation effects remain under 1 dB at both frequencies regardless of radome type for rainfall rates up to 10 mm/Hr. S-Band losses with a hydrophobic radome such as that on the WSR-88D remain under 1 dB up to 100 mm/Hr. C-Band losses on standard radomes such as that on the Patrick AFB WSR-74C can reach as much as 5 dB at 50 mm/hr.

In addition, calculations were performed to determine the reduction in effective reflectivity, Z, when a radar target is smaller than the sampling volume of the radar. Results are presented for both the Patrick Air Force Base WSR-74C and the WSR-88D as a function of target size and range.

Introduction

Beginning in 1999, the Kennedy Space Center sponsored an Airborne Field Mill (ABFM) experiment in support of its Lightning Launch Commit Criteria (LLCC) project. The LLCC project is designed to improve the weather constraints (launch commit criteria) designed to protect space launch vehicles, including the Space Shuttle, from harm. If these constraints are violated, launch must be delayed or scrubbed until the weather improves. The first ABFM field campaign took place in June 2000 (Merceret and Christian, 2000). A second field campaign was conducted in February 2001 and a third in May-June 2001.

The goal of the LLCC project is to use the ABFM measurements to learn enough about the behavior of electric charge in and near clouds to safely relax the current LLCC. Although the current constraints are safe, they have a false alarm (rule violated when it would actually be safe to fly) of more than 80 percent in some cases (Hugh Christian, NASA/Marshall Spaceflight Center, private communication). This is due primarily to our ignorance of how charge behaves in the atmosphere compounded by the need for large margins to ensure safety where there is no room for error The LLCC project is directed at reducing the ignorance component of this situation so that less restrictive yet even safer rules may be developed.

A key component of the experimental design is to couple ground-based weather radar measurements with *in-situ* cloud physics and electric field measurements from an instrumented aircraft. Details are presented in Merceret and Christian (2000). There are two operational weather radars used by the Eastern Range for launch, landing and ground operations support and both were available during the ABFM field campaigns. These radars are the NWS WSR-88D (NEXRAD) S-Band (3 GHz, 10 cm) radar located in Melbourne, Florida and the Air Force WSR-74C C-Band (6 GHz, 5 cm) unit located at Patrick AFB, FL. Thus this research concentrated on those wavelengths.

During the initial analysis of the ABFM data, it became apparent that in some cases the measured radar reflectivity of distant storms was too low. In most cases there were obviously intervening high reflectivity areas that would attenuate the radar beam between the radar and the more distant target. The discussion of the attenuation issue broadened to include concerns that heavy rain at either of the two radar sites could impose attenuation due to wetting of the radomes. This could degrade the accuracy of the research data collected by the LLCC program and also could be significant for operational use of the radars to evaluate current or improved LLCC. A similar reduction in measured reflectivity could occur if the target cloud was smaller than the radar sampling volume.

The author searched the literature to determine the significance of the "wet radome effect" at C and S band frequencies and, if possible, present quantitative estimates of these effects. Although the literature on the subject is limited, there was enough information available to provide such an estimate. The effect of sampling volume was determined analytically.

Part 1. Wet Radome Effects.

Methodology

The literature search began with the internet. Standard search engines were used in addition to a word search of the American Meteorological Society (AMS) publications database. All promising references were ordered from the library or located on-line and printed. Each was read to determine if they contained useful information. In some cases the authors were contacted by phone or email for additional information. The bibliographies of the publications located in this manner were scanned for additional leads that were also ordered and read. Those papers containing useful information are listed in the References section of this report.

One of the sources (AFC, 2002) was especially useful, and the author extracted the data they presented in order to generate an empirical formula for two-way losses as a function of rainfall rate and transmission frequency for both standard and hydrophobic radomes. Details are presented in the section describing the formula.

Literature Search Results

There were two classes of relevant information: qualitative and quantitative. The qualitative results are easily summarized since only two papers of this kind were found. Klazura (1981) reported that at C-Band, two-way losses from a radome wetted by heavy rain are not significant. He provided no detail on the type of radome used. Smith and Krajewski (1991) reported that WSR-88D (S-Band) losses can be kept small compared to other error sources. The WSR-88D uses a hydrophobic radome.

The best quantitative source of information was a commercial website presented by Antennas for Communications (AFC, 2002). They presented one-way radome losses for two types of radomes: "standard" and hydrophobic. They showed graphs of transmission loss (dB) as a function of rain rate (mm/Hr) at 14 GHz. They also showed transmission loss as a function of frequency (0 - 20 GHz) for a rain rate of 20mm/Hr. These data were used to generate the empirical formula described in the next section. The other quantitative sources typically provided "spot" values or upper bounds on attenuation at a range of rain rates or for rain rates describes only qualitatively. The results are presented in Table 1 and graphically in Figures 1 and 2.

With the exception of Effenberger and Strickland (1986) the data are mutually consistent within a dB or so for each radome type over a wide range of rainfall rates. The Effenberger and Strickland data are based on laboratory studies and computer simulations of flat panels held at 30 degrees from the vertical while being sprayed with water. They detected no significant variation of attenuation with spray intensities equivalent to from 10 to 50 mm/hr.

Source	Band (C or S)	Two-Way Loss (dB)	Notes
AFC, 2002	both	S: 0.35 standard, 0.1 hydrophobic. C: 1.15 standard, 0.3 hydrophobic	20 mm/Hr
Ryzhkov and Zrnic, 1995	S	2	WSR-88D under "heavy rain"
Effenberger and Strickland, 1986	both	S: 2 standard, 0.3 hydrophobic. C: 5 standard, <0.8 hydrophobic	Laboratory study and computer simulations equivalent to 15 mm/hr
Wilson, 1978	C	< 2 standard	10 mm/Hr
Joy and Wilson, 1986	both	S: 2.5 standard, 0.7 hydrophobic. C: 5 standard, 1 hydrophobic	Theoretical and limited laboratory analysis equivalent to 10 - 50 mm/Hr
Manz *et al.*, 1998	both	S: 1.5 standard, 0.3 hydrophobic C: 4 standard, 0.5 hydrophobic.	Theoretical calculations 10 mm/hr
Manz *et al.*, 1999; Loffler-Mang and Gysi, 1998	C	5 hydrophobic	Both papers use the same data derived from artificial rain equivalent to 300 mm/hr
Evans and Wolfson 2000	C	up to 20 on seriously degraded hydrophobic	50 to >200 mm/hr

Table 1. Results of the literature search for quantitative data.

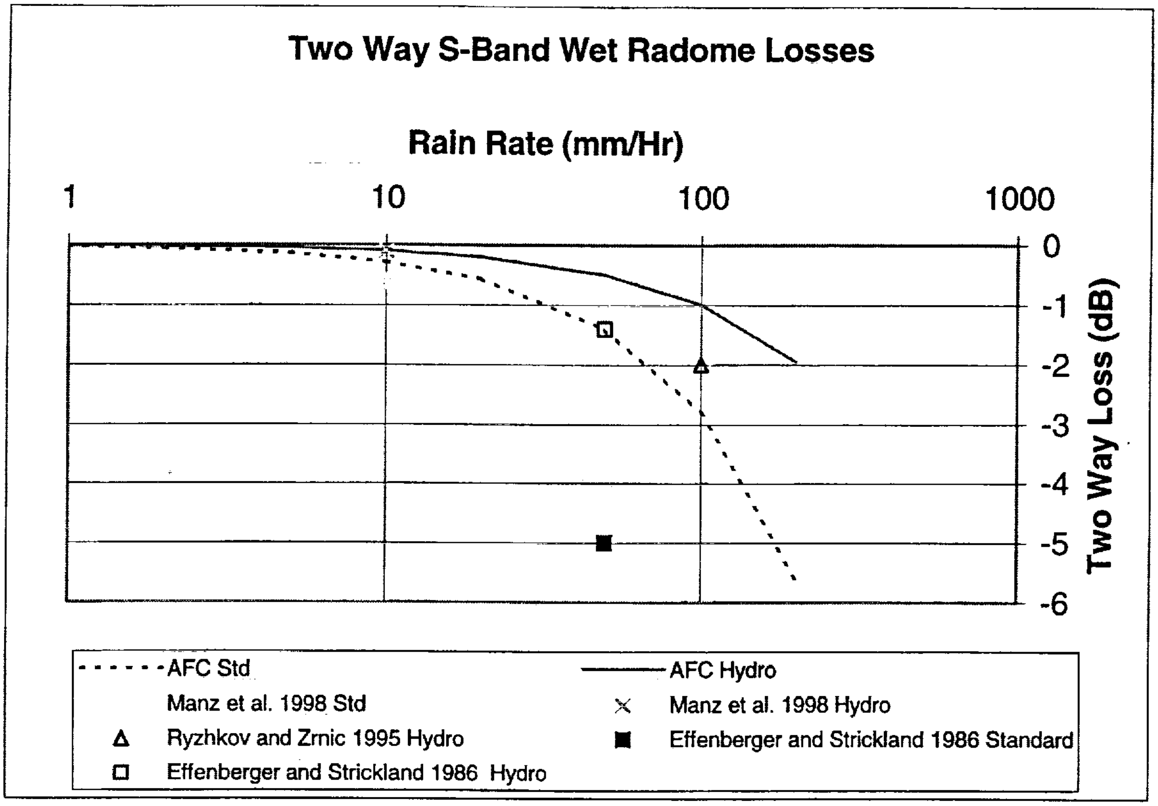

Figure 1. S-Band attenuation from the literature. The curve shown for AFC is extrapolated from the AFC data using the author's empirical formula described in the next section.

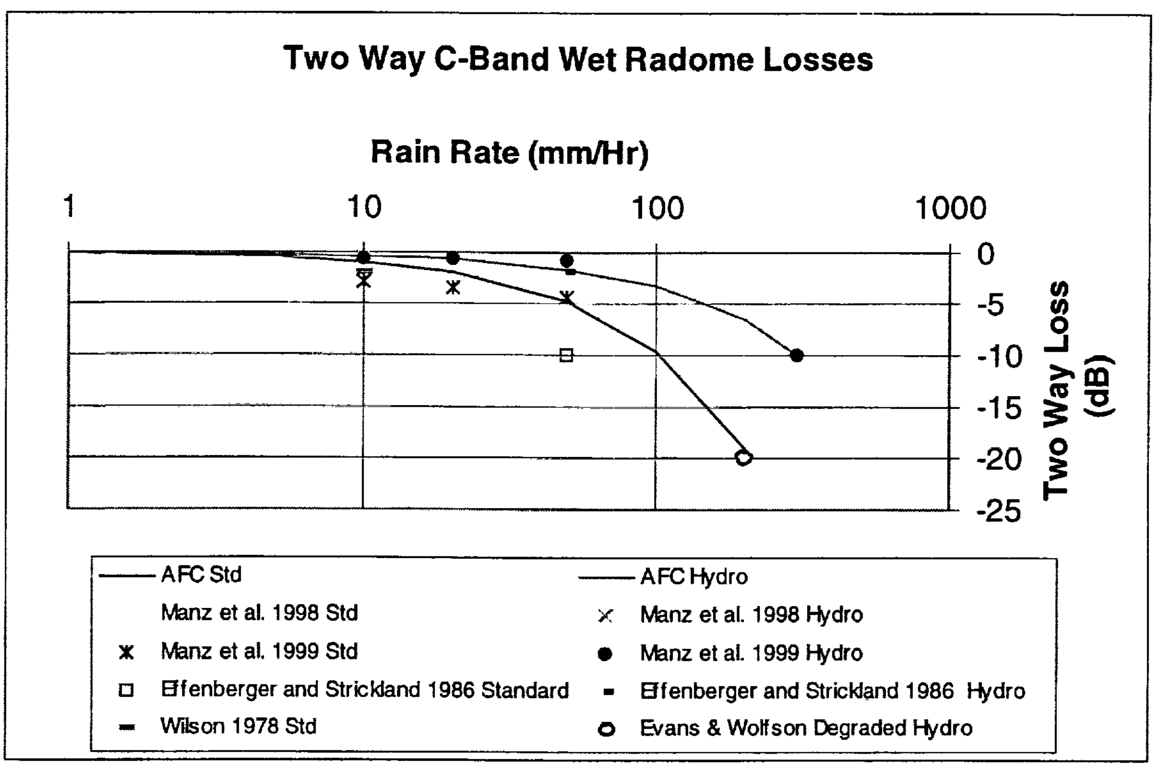

Figure 2. C-Band attenuation from the literature. The curve shown for AFC is extrapolated from the AFC data using the author's empirical formula described in the next section.

An Empirical Formula

The figures presented by AFC (2002) clearly indicated that the additional transmission loss due to radome wetting at 14 GHz was linearly proportional to rainfall rate with the constant of proportionality being significantly larger for the standard radome material than for the hydrophobic material. The figures also clearly demonstrated that at 20 mm/Hr the variation with frequency was monotonic with higher losses at higher frequencies. This suggested a model of the following form.

$$L = C\,R\,F(f) \qquad (1)$$

where L is the two-way transmission loss in dB due to radome wetting, R is the rainfall rate in mm/Hr and f is the frequency in GHz. F is a monotonic increasing function to be determined.

Using the AFC (2002) figure for the 20 mm/Hr attenuation as a function of frequency, a functional form for F was determined by trial and error which fit all of the AFC data to within 1 dB when substituted into equation 1 with the following result.

$$L = C\,R\,\tanh^2(f/10) \qquad (2)$$

where C = 0.165 for standard radomes and C = 0.0575 for hydrophobic radomes.

The two-way losses (dB) for S-Band and C-Band computed from the formula are presented in Table 2.

Rain Rate (mm/Hr)	S-Band Hydrophobic	S-Band Standard	C-Band Hydrophobic	C-Band Standard
1	0.01	0.03	0.03	0.10
2	0.02	0.06	0.07	0.19
5	0.05	0.14	0.17	0.48
10	0.1	0.28	0.33	0.95
20	0.2	0.56	0.66	1.9
50	0.49	1.4	1.66	4.8
100	0.98	2.8	3.32	9.5
200	1.95	5.6	6.63	19

Table 2. Attenuation as a function of rain rate for standard and hydrophobic radomes at S-Band and C-Band based on the empirical formula.

Conclusions

Several conclusions are readily apparent. First, hydrophobic radomes produce much smaller losses when wet than the standard ones. The radome on WSR-88D systems is hydrophobic (David Sharp, NWS/Melbourne FL, private communication) , so the data for the S-Band hydrophobic case presented here should be applied to evaluating attenuation effects on that radar. The radome on the Eastern Range WSR-74C is standard (Hal Herring, Eastern Range Technical

Services Contractor, private communication), so the C-Band standard data should be used to evaluate that radar.

Second, in light rain, the attenuation effects are small and remain under 1 dB even for the standard radome at C-Band until 10 mm/Hr is reached. For the WSR-88D, the effects are less than 1 dB up to 100 mm/Hr and do not exceed 2 dB at 200 mm/Hr which is rarely ever encountered even in Florida thunderstorms. On the other hand, the WSR-74C with the standard radome will see about 5 dB of round-trip attenuation at 50 mm/hr. 50 mm/Hr is extremely heavy rain, but not rare in Florida thunderstorms. This could be reduced by about a factor of three by coating the radome with a hydrophobic substance if the coating were properly maintained.

Finally, an empirical formula has been developed which can be used to estimate two-way wet radome losses over the range from 0-200 mm/Hr and 0-20 GHz for both types of radomes. The formula gives results within 1 dB of the AFC (2002) data at frequencies and rain rates presented at the AFC website. These data, in turn, are consistent within about 1 dB of the available data in the literature except for Effenberger and Strickland (1986) which are several dB higher based on laboratory and modeling data.

Since the Melbourne WSR-88D and the Patrick WSR-74C are located far enough apart that frequently rainfall will not affect both at the same time, a possible diagnostic for serious rainfall attenuation would be a systematic difference between the two radars over a number of targets at different ranges and azimuths. If the "wet" radar has consistently lower values, it would suggest that attenuation is occurring and may even provide quantitative guidance about its magnitude. The largest difference should occur with heavy rain over the 74C and none over the 88D.

Part 2. Beam Filling Effects

Analysis

The power returned from a transmitted weather radar pulse is directly proportional to the number of scatterers in the sampling volume so long as the relative size distribution is held constant (Doviak and Zrnic 1993, section 4.4). If a target such as a cloud does not fill the sampling volume, the number of particles in the volume is less than the number that would be present if the volume were completely filled by the same particle density and distribution. Thus the measured reflectivity will be equal to the actual reflectivity multiplied by the ratio of the target volume within the sampling volume to the total sampling volume. Thus, if the target fills half the volume, the reflected power will be 3 dB lower than if the volume had been filled.

The radar sample volume depends on the effective beam width, the pulse length, and the range. For the WSR-88D and WSR-74C, these parameters are presented in table 3.

Radar	WSR-88D	WSR-74C
Beam Width (degrees)	0.95	1.6
Beam Width (radians)	0.0166	0.028
Pulse Length (μs)	1.57	3
Pulse Length (Km)	0.47	0.9

Table 3. Beam volume-determining parameters for the WSR-88D and Patrick AFB WSR-74C.

The beam width in Km is equal to the beam width in radians times the range in Km. The beam filling loss in dB is given by

Loss (dB) = 10 log F (3)

where F is the fraction (<1) of the sampling volume filled by the target. This depends on the radar parameters, the range and the size of the target both along and perpendicular (both horizontally and vertically) to the beam.

For real targets, this becomes impossibly complex to evaluate precisely. Fortunately, precision is not required since for phenomena and ranges of practical interest to evaluating lightning launch commit criteria, beam filling is not a significant issue. The tables below present the results for targets from 0.2 to 6 KM in size at ranges from 10 to 200 Km for both radars.

Beam-filling "loss" (dB) as a function of feature size and range

	Lateral or vertical extent of feature (Km)							
Range (Km)	0.2	0.5	1	2	3	4	5	6
10	-1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	-4.5	-0.5	0.0	0.0	0.0	0.0	0.0	0.0
30	-6.2	-2.2	0.0	0.0	0.0	0.0	0.0	0.0
40	-7.5	-3.5	-0.5	0.0	0.0	0.0	0.0	0.0
50	-8.4	-4.5	-1.4	0.0	0.0	0.0	0.0	0.0
60	-9.2	-5.3	-2.2	0.0	0.0	0.0	0.0	0.0
70	-9.9	-5.9	-2.9	0.0	0.0	0.0	0.0	0.0
80	-10.5	-6.5	-3.5	-0.5	0.0	0.0	0.0	0.0
90	-11.0	-7.0	-4.0	-1.0	0.0	0.0	0.0	0.0
100	-11.4	-7.5	-4.5	-1.4	0.0	0.0	0.0	0.0
110	-11.9	-7.9	-4.9	-1.9	-0.1	0.0	0.0	0.0
120	-12.2	-8.3	-5.3	-2.2	-0.5	0.0	0.0	0.0
130	-12.6	-8.6	-5.6	-2.6	-0.8	0.0	0.0	0.0
140	-12.9	-8.9	-5.9	-2.9	-1.2	0.0	0.0	0.0
150	-13.2	-9.2	-6.2	-3.2	-1.4	-0.2	0.0	0.0
160	-13.5	-9.5	-6.5	-3.5	-1.7	-0.5	0.0	0.0
170	-13.8	-9.8	-6.8	-3.8	-2.0	-0.7	0.0	0.0
180	-14.0	-10.0	-7.0	-4.0	-2.2	-1.0	0.0	0.0
190	-14.2	-10.3	-7.2	-4.2	-2.5	-1.2	-0.3	0.0
200	-14.5	-10.5	-7.5	-4.5	-2.7	-1.4	-0.5	0.0

Note: Losses (dB) for lateral and vertical beam filling must considered separately. Vertical, lateral and radial losses must be added to get the total loss (dB).

	Radial extent of feature (Km)							
Range (Km)	0.2	0.5	1	2	3	4	5	6
ALL	-6.5	-2.6	0.0	0.0	0.0	0.0	0.0	0.0

Table 4. Beam filling “losses” for the WSR-74C as a function of range and target size.

Beam-filling "loss" (dB) as a function of feature size and range

Range (Km)	Lateral or vertical extent of feature (Km) 0.2	0.5	1	2	3	4	5	6
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	-2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	-4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	-5.2	-1.2	0.0	0.0	0.0	0.0	0.0	0.0
50	-6.2	-2.2	0.0	0.0	0.0	0.0	0.0	0.0
60	-7.0	-3.0	0.0	0.0	0.0	0.0	0.0	0.0
70	-7.6	-3.7	-0.6	0.0	0.0	0.0	0.0	0.0
80	-8.2	-4.2	-1.2	0.0	0.0	0.0	0.0	0.0
90	-8.7	-4.7	-1.7	0.0	0.0	0.0	0.0	0.0
100	-9.2	-5.2	-2.2	0.0	0.0	0.0	0.0	0.0
110	-9.6	-5.6	-2.6	0.0	0.0	0.0	0.0	0.0
120	-10.0	-6.0	-3.0	0.0	0.0	0.0	0.0	0.0
130	-10.3	-6.3	-3.3	-0.3	0.0	0.0	0.0	0.0
140	-10.6	-6.7	-3.7	-0.6	0.0	0.0	0.0	0.0
150	-10.9	-7.0	-4.0	-0.9	0.0	0.0	0.0	0.0
160	-11.2	-7.2	-4.2	-1.2	0.0	0.0	0.0	0.0
170	-11.5	-7.5	-4.5	-1.5	0.0	0.0	0.0	0.0
180	-11.7	-7.8	-4.7	-1.7	0.0	0.0	0.0	0.0
190	-12.0	-8.0	-5.0	-2.0	-0.2	0.0	0.0	0.0
200	-12.2	-8.2	-5.2	-2.2	-0.4	0.0	0.0	0.0

Note: Losses (dB) for lateral and vertical beam filling must considered separately. Vertical, lateral and radial losses must be added to get the total loss (dB).

Range (Km)	Radial extent of feature (Km) 0.2	0.5	1	2	3	4	5	6
ALL	-3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 5. Beam filling "losses" for the WSR-88D as a function of range and target size.

Clouds smaller than 1Km in extent are unlikely to be significant factors in making a go/no-go evaluation of a lightning launch commit criterion. Both radars are within 40 Km of the most distant launch complex at KSC/CCAFS near which the LLCC are to be evaluated. Under these constraints, the beam filling losses are less than 1dB for either radar.

Conclusion

Beam filling losses are not a significant constraint to using the Melbourne WSR-88D or the Patrick WSR-74C for LLCC evaluation in the immediate vicinity of KSC and CCAFS. They could become a factor if attempting to use the Melbourne or Jacksonville or Tampa WSR-88D radars to evaluate distant cloud complexes approaching from the north and west where the range from the feature to the radar exceeds 100 Km.

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13. ABSTRACT (Maximum 200 Words)

A search of scientific literature, both printed and electronic, was undertaken to provide quantitative estimates of attenuation effects of rainfall on weather radar radomes. The emphasis was on C-band (5 cm) and S-Band (10 cm) wavelengths. An empirical model was developed to estimate two-way wet radome losses as a function of frequency and rainfall rate for both standard and hydrophobic radomes. The model fits most of the published data within +/- 1dB at both target wavelengths for rain rates from less than ten to more than 200 mm/hr. Rainfall attenuation effects remain under 1 dB at both frequencies regardless of radome type for rainfall rates up to 10 mm/Hr. S-Band losses with a hydrophobic radome such as that on the WSR-88D remain under 1 dB up to 100 mm/Hr. C-Band losses on standard radomes such as that on the Patrick AFB WSR-74C can reach as much as 5 dB at 50 mm/hr.

In addition, calculations were performed to determine the reduction in effective reflectivity, Z, when a radar target is smaller than the sampling volume of the radar. Results are presented for both the Patrick Air Force Base WSR-74C and the WSR-88D as a function of target size and range.

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