

CRREL

REPORT 88-11

AD-A200 378

*Atmospheric icing
and broadcast antenna reflections*

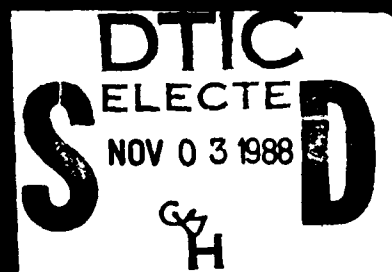


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**US Army Corps
of Engineers**

Cold Regions Research &
Engineering Laboratory

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CRREL Report 88-11

August 1988

Atmospheric icing and broadcast antenna reflections

Charles C. Ryerson

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No 0704-0188 Exp Date Jun 30, 1986	
1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) CRREL Report 88-11			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Cold Regions Research and Engineering Laboratory		6b. OFFICE SYMBOL (if applicable) CECRL	7a. NAME OF MONITORING ORGANIZATION Office of the Chief of Engineers		
6c. ADDRESS (City, State, and ZIP Code) Hanover, New Hampshire 03755-1290			7b. ADDRESS (City, State, and ZIP Code) Washington, D.C. 20314-1000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO 4A1611 02AT24	TASK NO FS
					WORK UNIT ACCESSION NO 005
11. TITLE (Include Security Classification) Atmospheric Icing and Broadcast Antenna Reflections					
12. PERSONAL AUTHOR(S) Ryerson, Charles C.					
13a. TYPE OF REPORT		13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) August 1988		15. PAGE COUNT 19
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES (			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Antenna icing \ Ice detectors		
			Atmospheric icing Mount Mansfield		
			Commercial broadcasters Mount Washington		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) This study assesses the effects of atmospheric icing on broadcast transmission reflections on two mountains—Mount Mansfield in northern Vermont and Mount Washington in New Hampshire. Experience and theory suggest that antenna ice accretions produce large signal reflections. Correlations between reflection coefficients and ice accretions on Rosemount ice detectors adjacent to antennas were low and occasionally negative. The unexpected correlations may be due to factors not measured, such as antenna tuning, ice type and ice location on the antenna system. Other confounding factors may include ice detector performance and methods used to compute antenna ice accretions from the ice detectors.					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Charles C. Ryerson			22b. TELEPHONE (Include Area Code) 603-646-4100		22c. OFFICE SYMBOL CECRL-RS

PREFACE

This report was prepared by Dr. Charles C. Ryerson, Research Physical Scientist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Office of the Chief of Engineers under Project Number 4A161102AT24, *Research in Snow, Ice and Frozen Ground*, Task Area FS, Work Unit 005, *Cold Regions Meteorological Processes*.

Walter Tucker III and Stephen Ackley of the CRREL Snow and Ice Branch actively provided encouragement and advice. John Govoni, Nathan Mulherin and Steven Arcone, also of the CRREL Snow and Ice Branch, facilitated data acquisition, critiqued manuscript drafts and supplied guidance concerning signal reflections from transmitter antennas. Edward Salvas and Ted Teffner of Mount Mansfield Television, Marty Engstrom and Art Dunlap of WHOM-FM on Mount Washington, and Brian Marshall and Ronald Whitcomb of Vermont Educational Television provided data and made suggestions concerning the interaction of radio and television transmissions and antenna icing. Richard Cushman of WHOM-FM and Peter Martin of WCAX-TV provided permission to use each station's antenna reflection measurements.

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Atmospheric Icing and Broadcast Antenna Reflections

CHARLES C. RYERSON

INTRODUCTION

Radio and television antennas transmit radio frequency (RF) energy with less than complete efficiency; some is reflected back to the transmitter from the antenna via the coaxial system. These reflections are expressed as a percentage of the total power sent to the antenna, and they represent energy not broadcast into the atmosphere (Kraus 1953, NAB 1985).

Transmitter operators observe that antenna ice accretion increases RF reflections (NAB 1985).^{*} The snow, ice and water that can surround or coat an antenna are insulating dielectrics capable of reflecting a portion of the electromagnetic energy fed to the antenna back through the waveguide system to the transmitter (Considine 1983). One measure of the capability of dielectric materials to reflect RF energy is their relative permittivity, which is a function of temperature, broadcast frequency and the type, density and purity of the material (Kraus 1953, Considine 1983). Dielectrics with small permittivities generally transmit RF energy more efficiently. Dry air at sea level has a permittivity very close to one, the value of a vacuum. Pure ice has a permittivity of about 3.2; the permittivity is slightly higher if impurities are present. The permittivity of rime varies between 2.0 and 3.1 depending upon ice density and age (Janowiak 1959, Langer 1959, Kuroiwa 1962, Evans 1965). Snow permittivity varies with liquid water content but usually falls between 1.4 for dry snow at density 0.25 and approximately 5.0 for wet snow (Hallikainen et al. 1982). Pure water at 0°C has a permittivity of about 88 (Reitz et al. 1979). (All quoted permittivities are dimensionless numbers and are for frequencies transmitted by the broadcasting facilities used in this study.)

Commercial broadcast antennas are usually designed and tuned to radiate most efficiently when surrounded with dry air and not ice, snow or

water. Though reflections are created when RF energy passes through the antenna/air interface, they are minimized by careful tuning of the antenna. Meteorological coatings for which the antenna is not tuned, such as ice or snow, cause electrical load imbalances and larger reflections. These reflections can cause transmitter overloads, leading to loss of power or signal quality or both. The amount, location and type of material coating the antenna affects the degree of detuning. For example, antennas are usually more severely detuned by wet, melting ice than by dry, low-density rime. In addition, detuning changes antenna spatial radiation patterns and increases delay distortion, causing ghosts in television images (Asami et al. 1958, Kuroiwa 1962).

Radomes and heaters reduce the effects of ice on antennas. Heaters are often controlled by automatic ice detectors such as probes that cyclically accrete and shed ice (Mulherin 1986). Though usually employed only to detect the presence of ice, detectors can be used to estimate relative accretion amounts from one icing period to another.

This study addresses relationships between antenna reflection coefficients as measured by commercial broadcasters, and antenna ice accretions as estimated from ice detectors, on two mountains—Mount Mansfield in northern Vermont and Mount Washington in New Hampshire. The study assesses the strength of relationships between reflections and ice as suggested by operators and theory, and the potential of using antenna reflection records as surrogates for icing records where reflections are measured regularly but icing may not be measured. The study period encompasses December 1982 through May 1986 on Mount Mansfield and December 1984 through May 1986 on Mount Washington (Table 1).

DATA SOURCES

Study location and icing conditions

Mount Mansfield (44°33'N, 72°49'W) in the

^{*} Personal communication with M. Engstrom, WHOM-FM, and E. Salvat and T. Teffner, Mount Mansfield Television.

Table 1. Icing and reflection coefficient record: Mt. Mansfield and Mt. Washington.

<i>Mt. Mansfield</i>				<i>Mt. Washington</i>			
<i>Begin</i>		<i>End</i>		<i>Begin</i>		<i>End</i>	
<i>Date</i>	<i>Time</i>	<i>Date</i>	<i>Time</i>	<i>Date</i>	<i>Time</i>	<i>Date</i>	<i>Time</i>
Icing measurements (Rosemount)							
10 Dec 82	1400	9 Jan 83	0300	27 Dec 84	0100	15 Jun 85	2400
14 Jan 83	1200	25 Feb 83	0400	24 Nov 85	0100	9 May 86	2400
26 Feb 83	0100	6 Apr 83	0800				
10 Apr 83	1800	8 May 83	1200				
29 Oct 83	1800	22 May 84	2400				
21 Oct 84	0100	21 Dec 84	1300				
22 Dec 84	2000	18 Feb 85	0100				
24 Feb 85	1900	20 May 85	2400				
2 Nov 85	1700	26 Apr 86	0500				
27 Apr 86	1600	26 May 86	1600				
Reflections computed from VSWR							
10 Dec 82	—	11 Mar 83	—	27 Dec 84	—	15 Jun 85	—
19 Mar 83	—	8 May 83	—	24 Nov 85	—	9 May 86	—
29 Oct 83	—	15 Nov 83	—				
19 Nov 83	—	29 Nov 83	—				
10 Dec 83	—	8 Jan 84	—				
2 Feb 84	—	17 Mar 84	—				
23 Mar 84	—	22 May 84	—				
21 Oct 84	—	22 Nov 84	—				
27 Nov 84	—	20 May 85	—				
2 Nov 85	—	25 Mar 86	—				
28 Mar 86	—	16 May 86	—				
22 May 86	—	26 May 86	—				
Reflections measured at transmitter							
10 Dec 82	0600	30 Apr 83	2400				
1 Dec 83	0600	16 May 84	2400				
21 Oct 84	0100	20 May 85	2400				
1 Nov 85	0100	26 May 86	2400				

Green Mountains of Vermont, and Mount Washington (44°16'N, 71°18'W) in the White Mountains of New Hampshire (Fig. 1), are located approximately 127 km apart. With elevations of 1339 and 1917 m, respectively, both Mount Mansfield and Mount Washington have

- frequent icing events for three seasons;
- continuously manned summit facilities for housing and maintaining instrumentation;
- four years of icing records from the same model of Rosemount ice detector (Ryerson 1988);
- summit radio and television transmission facilities where broadcast signal reflections are measured regularly.

Mount Mansfield and Mount Washington have quite different icing environments. Icing occurs approximately twice as frequently on Mount

Washington, with intensities over 12 times greater, ice accumulations over 25 times greater, and events about twice as long as on Mount Mansfield. Icing occurs approximately 13–17% of the time of Mount Mansfield and 39% of the time on Mount Washington during winter and spring. Icing periods average about five hours in length on Mount Mansfield and about 12 hours in length on Mount Washington. Ice-free periods on the two peaks average about 19–25 hours (Ryerson 1988).

Icing data

Mount Mansfield

Time and intensity of icing events were obtained from a Model 871CB1 Rosemount ice detector owned and operated by Vermont Educational Television (VTETV) for automatic antenna heater

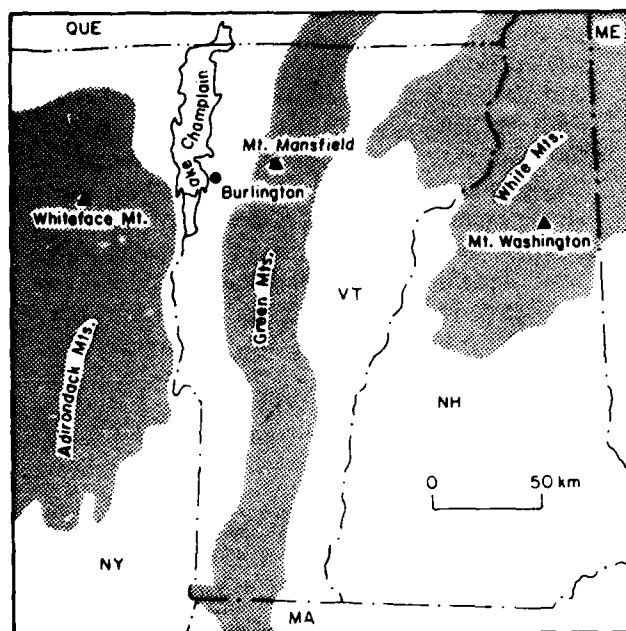


Figure 1. Locations of Mount Mansfield and Mount Washington.

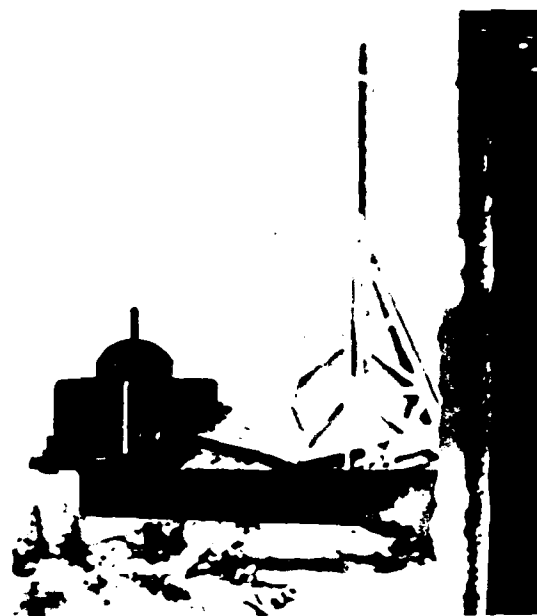


Figure 2. Rosemount Model 871CB1 detector on VTETV tower.

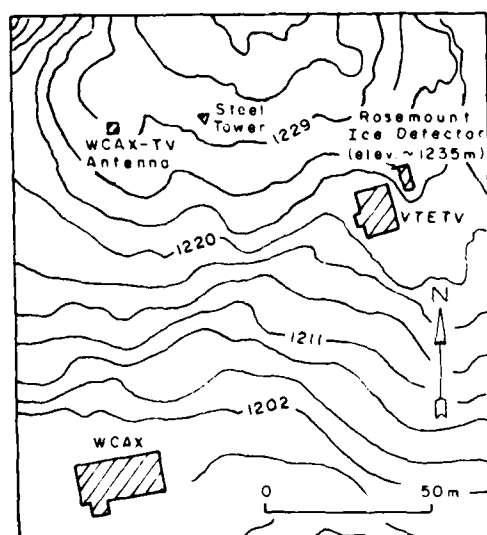


Figure 3. Relative locations of VTETV ice detector and WCAX-TV antenna on Mount Mansfield.

control (Ryerson 1987) (Fig. 2). The detector is mounted on a boom about 10 m above the ground surface on the northwest side of the VTETV microwave tower (detector elevation 1235 m), about 10 m lower in elevation than the base of the WCAX antenna mast, and about 100 m southeast of the WCAX antenna (Fig. 3). The detector senses ice accumulating on a 6- by 25-mm vertical

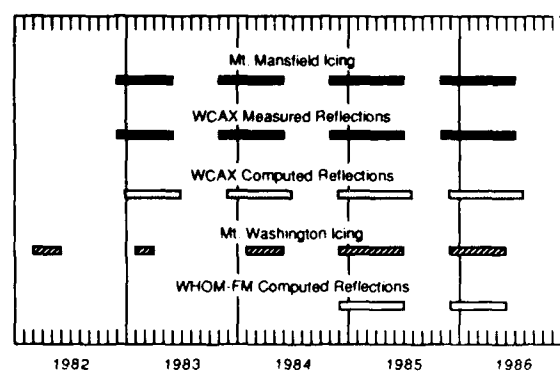


Figure 4. Icing and reflection data correspondence.

probe vibrating at 40 kHz. A frequency drop induced by the accreting ice mass activates a heater that melts accumulated ice from the probe and the dome at its base. Each heating, or deicing, cycle lasts 90 s and is recorded on a continuously operated event recorder. The Mount Mansfield icing records encompass four winters from December 1982 through May 1986 (Fig. 4, Table 1). Ice de-

tector deicing cycles transcribed and summed hourly from the recorder charts constitute the basis for all analyses.

Mount Washington

Icing was recorded from the same model Rosemount ice detector used on Mount Mansfield. The detector is mounted atop the well-exposed Mount Washington Observatory tower (about 20 m above the ground surface) at the same elevation and approximately 100 m from the WHOM-FM antenna (Tucker and Howe 1984) (Fig. 5).

Unlike on Mount Mansfield, the manner of operating the Mount Washington detector has ap-

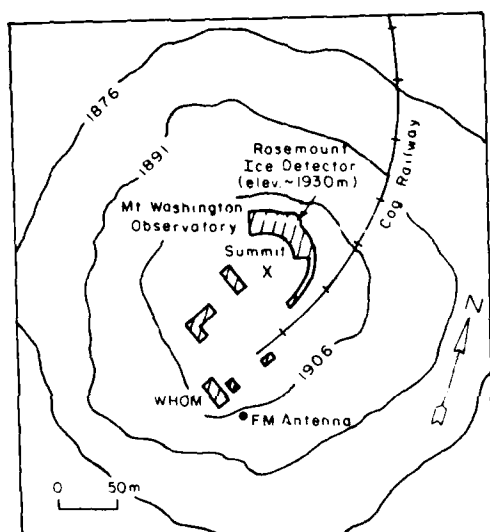


Figure 5. Relative locations of Mount Washington Observatory ice detector and WHOM-FM antenna on Mount Washington.

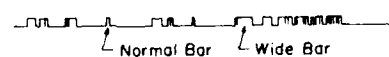
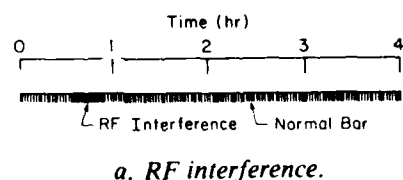


Figure 6. Rosemount ice detector icing cycles.

parently caused the loss of data. The detector is not operated when Observatory personnel judge that no icing is occurring. When icing is observed, the recorder is activated for only the event duration. Unfortunately observers may miss the beginning of many major icing events, or perhaps entire minor events, because they are busy with other duties or cannot see icing begin because of darkness. Therefore, a lesser degree of confidence can be placed on the Mount Washington record because of the inevitable data loss. In this study, periods when the ice detector was not operating between icing events were inferred as ice-free. Only periods when the detector was removed—during repairs or for the summer—were treated as missing.

Two additional problems plague the Mount Washington ice recordings. Television and radio transmission antennas on the mountaintop create a high-power RF environment. Though shielded against interference, the ice detector will occasionally respond erratically when RF signals penetrate its shielding. The resulting high-frequency signal, readily apparent and counted as missing on the recorder charts, occurred less than 1% of the time in the four years of record (Fig. 6a).

The second problem involves the ice detector deicing cycle. The heater remains in operation for 90 s even if all ice melts from the probe in the first 10 s of the cycle. Furthermore, because of the cycle length, a theoretical maximum of only 40 discrete cycles can occur per hour when the detector is operating at its maximum rate. According to Mount Washington Observatory personnel, higher icing rates may cause deicing cycles to overlap, producing bars wider than one 90-s cycle (Fig. 6b). These wide bars represent more than one cycle and suggest that detector saturation may be occurring (Tucker and Howe 1984).

This effect can also occur in light icing at very low temperatures.* Deicing may be incomplete and leave a finger of ice standing next to the probe. Recontact of the ice with the probe initiates a second deicing cycle before the first one is completed. This again creates a wide bar on the recorder chart, rather than a series of narrow 90-s bars, implying a greater icing rate than is actually occurring. Wide bars were created during less than 4% of the record period.

Each of these situations was treated differently when data were transcribed from the recorder

* Personal communication with J. Howe, Mount Washington Observatory.

charts. Periods of RF interference were removed. Wide bars created during high icing rates were counted as equivalent to rates occurring before and after the bar formed. Wide bars created during low icing rates were counted as one cycle. Though somewhat subjective, these rules of thumb were followed consistently throughout transcription. These problems were not apparent at Mount Mansfield, perhaps because icing is less severe there and because the recorder attached to the ice detector could not resolve deicing cycle length with the same precision as on Mount Washington.

Antenna reflection data

WCAX-TV (Mount Mansfield Television, Ch. 3, Video 61.25 MHz AM, Aural 65.75 MHz FM) on Mount Mansfield and WHOM-FM (94.9 MHz FM) on Mount Washington both measure antenna reflections. The WCAX-TV record spans the entire four-year period of icing measurements on the peak. The WHOM-FM record covers 18 months. WCAX-TV records hourly reflection values for both the visual and aural portions of their transmissions and a daily instantaneous composite value for both signals (Fig. 4, Table 1). WHOM-FM records reflections every three hours.

Reflections are either metered directly or computed from the Voltage Standing Wave Ratio (VSWR), a reflection-induced voltage in the transmitter-antenna waveguide. WCAX-TV measures aural and visual reflections individually from the transmitter-antenna coaxial cable as it exits the transmitter; VSWR is measured farther along the coaxial cable as a composite of the aural and visual signals. The signal is broadcast from a single-bay General Electric helix antenna (Jasik 1961). WHOM-FM measures VSWR only and broadcasts from a Shively five-bay ring antenna system with radomes.*

VSWR measurements were converted to reflection coefficients for consistency using eq 1 (Reich et al. 1957):

$$PR = [(VSWR - 1) / (VSWR + 1)] \times 100 \quad (1)$$

where PR is the reflection coefficient, which varies between 0 and 100 as VSWR varies from 1 to infinity.

* Personal communication with R. Surette, Shively Labs.

DATA PREPARATION

Several problems that complicated the correlation of reflections with icing and could be sources of error had to be considered before the data could be analyzed. First, antenna ice thickness could not be measured directly because the antennas were inaccessible. Thickness was estimated from ice detector records because the antennas and the ice detectors are exposed similarly. Second, WCAX-TV uses heaters to remove antenna ice. Heater usage was accounted for when estimating the antenna ice accretion from the ice detector records. Third, meteorological conditions that can remove ice, such as solar radiation and high winds (especially those shifting direction rapidly), could not be accounted for because measurements were unavailable. Fourth, when reflections become severe, WCAX-TV switches from a Harris to a General Electric transmitter. The two transmitters produce different reflection magnitudes for the same conditions and had to be analyzed individually.[†] Finally, antenna tuning was unknown and could produce confusing correlations because antennas in environments with frequent icing may be slightly detuned and create reflections when clear of ice, become optimally tuned with less reflection when slightly iced, and again detune and reflect more intensely when iced heavily.

The Rosemount ice detector deices when a specific mass, and thus thickness at a given density, of ice accumulates on the probe. As a result, Rosemount deicing cycles may serve as measures of ice accretion on adjacent antennas with similar exposure and collection efficiency. However, a simple sum of deicing cycles cannot represent ice accretion without accounting for the time when the ice detector probe is deicing and not accreting ice. As the deicing cycle rate increases, the proportion of time remaining for ice accretion on the unheated probe between cycles decreases. A correction for the constant 90-s deicing period devoted to melting ice from the probe each hour is expressed by the following:

$$PC = RC \times [1.0 + [RC / (40.0 - RC)]] \quad (2)$$

where PC is the proportional deicing cycles per hour, and RC is the recorded deicing cycles per hour.

[†] Personal communication with E. Salvas, Mount Mansfield Television.

Ice accretion is not a linear function of the sum of recorded deicing cycles because they represent only the amount of ice that accretes on the probe between deicing cycles. This is not a serious problem at low icing rates because deicing consumes only a small portion of each icing hour. However, at high icing rates a larger portion of each hour may be consumed for deicing than for icing. Since the deicing period is set at the factory to a constant 90 s, a theoretical maximum of 40 cycles can occur per hour with infinitely short accretion periods between deicing cycles. Equation 2 considers that portion of each hour devoted to deicing and computes a proportional cycling rate for a probe with an instantaneous deicing cycle that is infinitely short and does not subtract from the probe accretion time. Equation 2 assumes that the probe instantly heats, deices and recools to the ambient air temperature and provides the maximum icing rate that could occur on a bare ice detector probe.

Proportional hourly deicing cycle sums computed from eq 2 were used for all analyses. The product of *PC* and the probe trigger mass computes the potential mass accretion on the probe over time. However, mass accretion was used only for plots. Deicing cycles alone were sufficient for the statistical analyses because only relative, not absolute, icing values were needed for correlations with reflections.

Two additional problems affect the statistical comparisons of icing and antenna reflections. First, the effects of antenna ice type, location and thickness on reflections are poorly understood. They can be deduced theoretically, and they have been measured experimentally on specific antennas at specific frequencies, but generally operational effects in the field are not well understood (Thowless 1980). Second, the Rosemount ice detector only indirectly suggests, within its operational limits, the amount of ice on an antenna, and it provides no indication of ice type or location because of its location remote from the antenna.

Correlations were made between reflections and seven different estimates of antenna ice accretion. Each estimate of antenna ice accretion was made using a different method for converting proportional Rosemount deicing cycles to antenna ice amounts. Methods 1-4 attempt to simulate icing rates on the antenna during entire icing events rather than ice accretion. Method 1 simply leaves the proportional Rosemount deicing cycles for each hour unchanged, and reflections are correlated to these hourly values. Method 2 is identical to Method 1, except that hours with no icing are re-

moved from the data record. Method 3 uses a five-hour running mean of proportional deicing cycles to smooth rapid icing rate changes, whereas Method 4 uses a progressive mean that averages hourly proportional deicing cycles from the start of each icing event. Smoothing buffers the rapid icing rate fluctuations experienced by the small ice detector probe that may not be experienced by a large antenna, and the result could more realistically represent antenna icing rates.

Methods 5-7 attempt to simulate ice accretion amounts, rather than rates, through entire icing events because reflections are probably most responsive to ice accretion amounts. Method 5 progressively sums proportional Rosemount cycles through each icing event and assumes that a linear relationship exists between ice accretion and reflection magnitudes. Methods 6 and 7 compute the square and the common logarithm, respectively, of the summed event accretions from Method 5 as each event progresses. The square and logarithm may account for possible nonlinearities in the ice-reflection relationship. Periods of above-freezing temperatures, activated antenna heaters and reduced transmitter power were omitted from all computations. Also, the Harris and General Electric transmitter reflections at WCAX-TV were analyzed separately because they provided very different reflection magnitudes for the same conditions.

Antenna tuning could adversely affect the expected relationships between icing and reflections, especially under light icing conditions. It follows, then, that if low reflection magnitudes and their attendant icing values are removed and only higher magnitudes are correlated, a stronger relationship between icing and reflections might emerge. Therefore, icing was correlated with three sets of reflection data to produce 21 correlations for each transmitter signal. Each of the seven simulation methods was correlated with 1) all recorded antenna reflections, 2) a sample of antenna reflections greater than the mean reflection and 3) a sample of reflections greater than the mean reflection plus one standard deviation.

ANALYSES

In theory, and according to casual observation, antennas should create higher mean reflections when iced than when ice-free. In addition, reflections should be significantly larger during icing and not larger simply due to random chance. The

Table 2. Hourly reflections for both mountains.

	WCAX-TV					WHOM-FM
	Harris*		GE*		Composite†	
	Aural	Visual	Aural	Visual	Aural & visual	Aural†
Entire record period						
Mean	1.66	1.24	8.81	2.32	0.97	0.53
Median	2.00	1.00	9.00	2.00	0.83	0.27
Mode	2.00	1.00	10.00	2.00	0.83	0.15
Minimum	0.00	0.00	1.00	0.00	0.23	0.01
Maximum	11.00	7.00	19.00	8.00	3.37	3.01
Std. dev.	0.79	0.62	3.58	1.48	0.41	0.55
Total hours	12,351	12,351	923	923	575	1,364
Icing hours alone						
Mean	1.60	1.20	9.10	2.52	0.88	0.58
Median	1.50	1.00	9.00	2.00	0.83	0.32
Mode	1.00	1.00	10.00	2.00	0.83	0.15
Minimum	0.00	0.00	1.00	0.00	0.23	0.01
Maximum	9.00	7.00	19.00	8.00	2.22	3.01
Std. dev.	0.97	0.73	3.76	1.50	0.39	0.57
Total hours	1,935	1,935	226	226	106	917
Ice-free hours alone						
Mean	1.67	1.25	8.71	2.26	0.99	0.44
Median	2.00	1.00	9.00	2.00	0.83	0.19
Mode	2.00	1.00	9.00	2.00	0.83	0.15
Minimum	0.00	0.00	1.00	0.00	0.23	0.02
Maximum	11.00	6.00	19.00	8.00	3.37	2.78
Std. dev.	0.75	0.59	3.52	1.47	0.41	0.51
Total hours	10,416	10,416	697	697	469	447

* Measured directly from transmitter.

† Computed from measured VSWR.

expected relationships, however, did not always occur; reflections were frequently lowest during icing. Table 2 lists statistics for reflection magnitude for icing and ice-free hours together, icing hours alone and ice-free hours alone. Icing increased reflection magnitude at WHOM-FM on Mount Washington and at the WCAX-TV General Electric transmitter on Mount Mansfield. For example, mean reflections at WHOM-FM were 0.58 during icing and 0.44 during ice-free periods. However, WCAX-TV's Harris transmitter and composite aural and visual reflection measurements decreased during icing. The composite values averaged 0.88 and 0.99 during iced and ice-free periods, respectively.

Chi-square statistics were used to determine whether there were significant differences between iced and ice-free reflection magnitudes (Table 3). All reflections were considered significantly different when probabilities were smaller than 0.01. That is, relationships were considered as true if

they had less than 1% chance of occurring randomly. Table 3 indicates that the WCAX-TV General Electric transmitter reflections are slightly larger during icing and that the composite aural and visual reflections are smaller during icing. However, the small chi-square values of each, with probabilities larger than 0.01, indicate that iced and ice-free reflections are not significantly different. Conversely the WCAX-TV Harris transmitter iced and ice-free reflections are significantly different, as indicated by the large chi-square values and low probabilities, but again ice-free reflections are larger than iced reflections. Only the WHOM-FM reflection means perform as expected; iced reflections are significantly larger than the ice-free reflections.

Correlations also did not conform to expectations, being generally small and frequently negative. All WCAX-TV reflection correlations with Rosemount icing are low, many are negative and many are not significant (Tables 4-6). Correla-

Table 3. Reflection comparisons for iced and ice-free conditions.

	Chi ²	Prob.	N	Mean	S.D.
Computed reflections					
WHOM-FM					
Iced			917	0.58	0.57
Ice-free	38.94	0.000	447	0.44	0.51
WCAX-TV (composite aural and visual)					
Iced			106	0.88	0.39
Ice-free	4.14	0.042	469	0.99	0.41
Measured reflections					
WCAX-TV Harris visual					
Iced			1,935	1.20	0.73
Ice-free	47.23	0.000	10,416	1.25	0.59
WCAX-TV Harris aural					
Iced			1,935	1.60	0.97
Ice-free	40.47	0.000	10,416	1.67	0.75
WCAX-TV GE visual					
Iced			226	2.52	1.50
Ice-free	1.99	0.158	697	2.26	1.47
WCAX-TV GE aural					
Iced			226	9.10	3.76
Ice-free	0.17	0.678	697	8.71	3.52

Chi²—Chi-square statistic for two independent populations.

Prob.—Probability of Chi² statistics.

N—Number of cases compared.

Mean—Mean of cases compared.

S.D.—Standard deviation of cases compared.

tions become somewhat larger, though also frequently negative, when only reflections greater than the mean or the mean plus one standard deviation are correlated with ice. These larger and negative correlations, when significant, suggest that reflections may actually decrease as ice thickness increases. Only the WCAX-TV Harris visual reflection correlations became larger and positive when correlations were limited only to reflections greater than the mean plus one standard deviation.

Negative correlations suggest that ice may actually decrease reflections. There may be several reasons for this. The WCAX-TV antenna may not be optimally tuned for ice-free conditions but, as suggested earlier, could be tuned for slightly iced conditions. Ice-free conditions may produce tolerable reflections, but slight icing may actually lower reflections, and heavier icing may again raise reflections. In addition, the WCAX-TV antenna is a helix supported by a mast. The mast is surrounded by the helix and is electrically part of the antenna system. Heaters deice only the helix, not the mast. Ice remaining on the mast may produce high re-

flections, perhaps in part from liquid water created from ice melted from the helix.

The response of antenna reflections at WHOM-FM to Rosemount ice accretion was similar to that at WCAX-TV in some ways and different in others (Table 7). Correlations between all reflections and ice accretion are low to moderately positive, between 0.38 and 0.54, and statistically significant with probabilities less than 0.01. As with the WCAX-TV General Electric transmitter, correlations decrease when reflections greater than the mean and the mean plus one standard deviation are considered alone.

Frequency histograms of reflection coefficients during iced and uniced antenna conditions, and scatter plots of reflection coefficients with antenna ice thickness computed from the Rosemount ice detector, support conclusions implied by the statistics in the tables. Distributions of the WCAX-TV Harris transmitter aural and visual reflection coefficients are negatively skewed (Fig. 7). Most reflections during both iced and uniced conditions are small. The largest reflection magnitudes, though infrequent, are associated with icing. The scatter plots indicate that reflection coefficients are usually small during both heavy and light icing, and that large reflections are associated with smaller, rather than larger, estimated ice accretions (Fig. 8). This may be due to a variety of reasons other than ice thickness, such as ice density, free-water content of the ice, and ice position on the antenna radiating surface.

Frequency histograms of the WCAX-TV GE transmitter reflection coefficients are not as negatively skewed as are those of the Harris coefficients (Fig. 9). The largest reflections are not always associated with icing or, as with the Harris, with the largest ice accretions (Fig. 10). The histograms do suggest a somewhat greater frequency of high reflections during icing than during uniced conditions. The WCAX-TV composite aural and visual reflections that are based on VSWR measurements are similar to the Harris and GE patterns, though less clearly because of the smaller population of measurements (Fig. 11 and 12).

The WHOM-FM frequency histogram and scatter plot differ from those of WCAX-TV (Fig. 13 and 14). The frequency histogram is more negatively skewed, but as expected the negative skew of the uniced reflections is greater than that of the iced reflections. A greater portion of the iced reflections are higher in magnitude than are the uniced reflections. The scatter plot indicates that the largest ice accretions are usually associated with higher-

Table 4. Correlations of icing and measured reflections for the WCAX Harris transmitter on Mt. Mansfield.

Method	All reflections						Reflections > mean						Reflections > mean + 1 s.d.					
	Aural			Visual			Aural			Visual			Aural			Visual		
	r	Prob.	N	r	Prob.	N	r	Prob.	N	r	Prob.	N	r	Prob.	N	r	Prob.	N
Icing rate																		
1. All hours	-0.04	0.000	12,351	-0.02	0.009	12,351	0.11	0.000	1,783	0.10	0.000	1,783	-0.03	0.489	463	-0.06	0.220	463
2. Icing hours	-0.05	0.023	1,935	-0.01	0.572	1,935	-0.16	0.009	280	-0.03	0.649	280	-0.21	0.036	99	-0.10	0.345	99
3. Running mean	-0.03	0.152	2,213	-0.01	0.624	2,213	-0.17	0.001	352	0.03	0.532	352	-0.01	0.940	55	0.33	0.013	55
4. Prog. mean	0.00	0.987	2,213	0.03	0.120	2,213	-0.20	0.000	352	-0.01	0.870	352	-0.05	0.707	55	0.24	0.076	55
Ice accretion																		
5. Sum	-0.01	0.651	2,213	0.09	0.000	2,213	-0.09	0.086	352	-0.05	0.372	352	-0.02	0.897	55	0.45	0.001	55
6. Square	-0.03	0.101	2,213	0.09	0.000	2,213	-0.07	0.168	352	-0.03	0.637	352	-0.06	0.669	55	0.22	0.107	55
7. Log10	-0.01	0.782	2,213	0.06	0.007	2,213	-0.07	0.181	352	0.15	0.005	352	0.09	0.513	55	0.57	0.000	55

r—Correlation coefficient

Prob.—Correlation probability.

N—Number of cases correlated.

Running mean—Five-hour running mean of proportional deicing cycles per hour since beginning of event.

Prog. mean—Progressive mean of proportional deicing cycles per hour since beginning of event.

Sum—Progressive sum of proportional deicing cycles since beginning of event.

Square—Square of summed proportional deicing cycles since beginning of event.

Log10—Common logarithm of summed proportional deicing cycles since beginning of event.

Table 5. Correlations of icing and measured reflections for the WCAX GE transmitter on Mt. Mansfield.

Method	All reflections						Reflections > mean						Reflections > mean + 1 s.d.					
	Aural			Visual			Aural			Visual			Aural			Visual		
	r	Prob.	N	r	Prob.	N	r	Prob.	N	r	Prob.	N	r	Prob.	N	r	Prob.	N
Icing rate																		
1. All hours	0.06	0.094	923	0.07	0.047	923	-0.06	0.319	251	-0.13	0.042	251	-0.15	0.150	97	-0.11	0.288	97
2. Icing hours	0.06	0.354	226	0.04	0.543	226	-0.17	0.152	76	-0.19	0.102	76	-0.36	0.114	20	0.32	0.172	20
3. Running mean	-0.06	0.272	369	0.01	0.838	369	-0.27	0.002	131	-0.21	0.017	131	-0.32	0.051	39	0.10	0.565	39
4. Prog. mean	-0.14	0.009	369	-0.03	0.614	369	-0.24	0.005	131	-0.22	0.012	131	-0.25	0.121	39	0.04	0.792	39
Ice accretion																		
5. Sum	-0.09	0.091	369	0.02	0.640	369	-0.34	0.001	131	-0.29	0.001	138	-0.24	0.150	39	0.12	0.482	39
6. Square	-0.09	0.101	369	0.03	0.621	369	-0.35	0.001	131	-0.28	0.001	138	-0.30	0.061	39	0.16	0.340	39
7. Log10	-0.12	0.019	369	-0.03	0.558	369	-0.24	0.000	131	-0.24	0.006	138	0.04	0.817	39	-0.07	0.670	39

Same abbreviations as Table 4.

Table 6. Correlations of icing and reflections computed from VSWR for the WCAX-TV antenna on Mt. Mansfield.

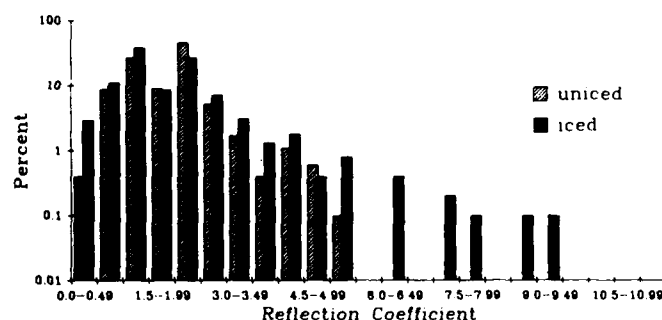
Methods	All reflections			Reflections > mean			Reflections > mean + 1 s.d.		
	r	Prob.	N	r	Prob.	N	r	Prob.	N
Icing rate									
1. All hours	-0.07	0.080	575	-0.03	0.672	186	0.03	0.840	65
2. Icing hours	-0.03	0.755	106	-0.06	0.731	28	0.22	0.568	9
3. Running mean	-0.07	0.489	109	-0.18	0.513	15	-0.18	0.513	15
4. Prog. mean	-0.11	0.269	109	-0.21	0.459	15	-0.21	0.459	15
Ice accretion									
5. Sum	-0.07	0.489	109	-0.07	0.806	15	-0.07	0.806	15
6. Square	-0.05	0.629	109	-0.13	0.647	15	-0.13	0.647	15
7. Log10	-0.08	0.420	109	0.09	0.741	15	0.09	0.741	15

Same abbreviations as Table 4.

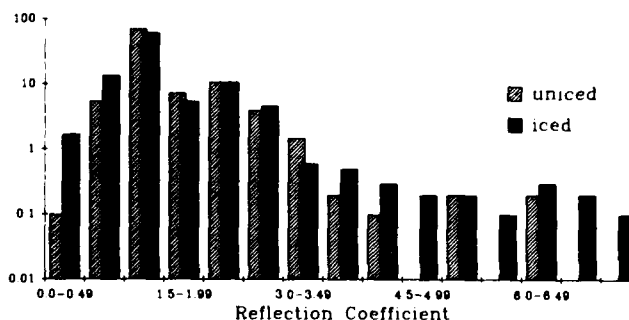
Table 7. Correlations of icing and reflections computed from VSWR for the WHOM-FM antenna on Mt. Mansfield.

Methods	All reflections			Reflections > mean			Reflections > mean + 1 s.d.		
	r	Prob.	N	r	Prob.	N	r	Prob.	N
Icing rate									
1. All hours	0.14	0.000	1364	-0.07	0.120	527	-0.20	0.013	147
2. Icing hours	0.12	0.000	917	-0.11	0.032	376	-0.21	0.024	114
3. Running mean	0.32	0.000	577	0.05	0.468	244	0.04	0.661	130
4. Prog. mean	0.44	0.000	577	0.08	0.197	244	0.09	0.309	130
Ice accretion									
5. Sum	0.54	0.000	577	0.32	0.000	244	0.18	0.042	130
6. Square	0.38	0.000	577	0.24	0.000	244	0.10	0.254	130
7. Log10	0.44	0.400	577	0.21	0.001	244	0.25	0.005	130

Same abbreviations as Table 4.

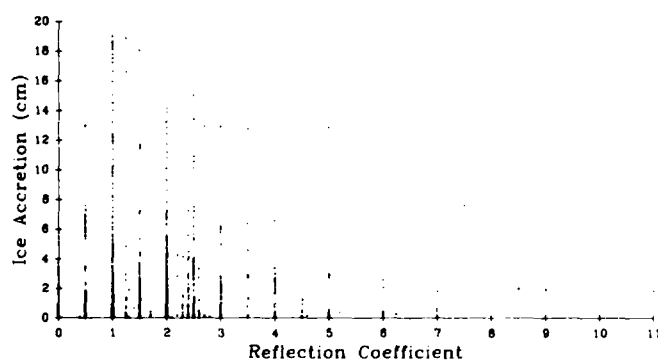


a. Aural signal reflections.

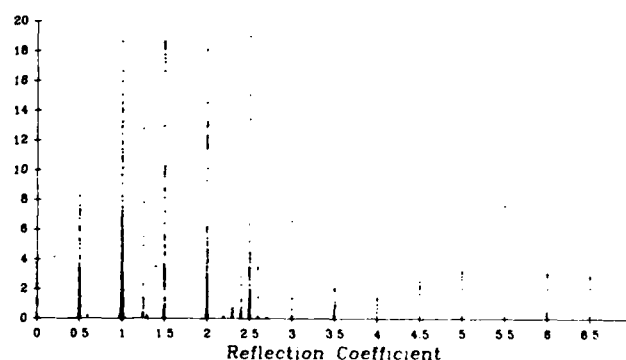


b. Visual signal reflections.

Figure 7. WCAX-TV Harris reflections during iced and uniced conditions.



a. Aural signal reflections.



b. Visual signal reflections.

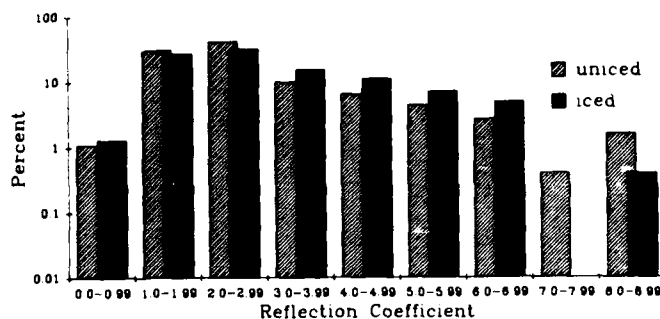
Figure 8. WCAX-TV Harris reflections and estimated antenna ice accretions.

magnitude reflection coefficients. But, as with WCAX-TV, even small amounts of ice can produce reflections of any magnitude. In other words, larger ice accretions usually increase reflections, whereas small amounts of ice can produce large or small reflections.

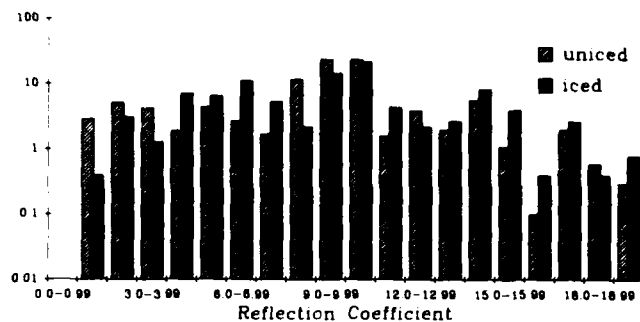
Antenna design may be one reason WHOM-FM produced higher correlations. The WHOM-FM

antenna system is a set of five-bay ring antennas enclosed by unheated radomes. Ice collects on the radomes, but reflections rarely become large because ice does not contact the radiating elements.* Because of their enclosed design and compact size, they are more uniformly and predictably affected

* Personal communication with R. Surette, Shively Labs.

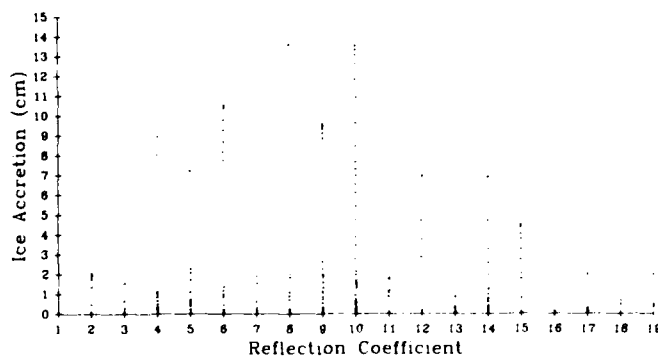


a. Aural signal reflections.

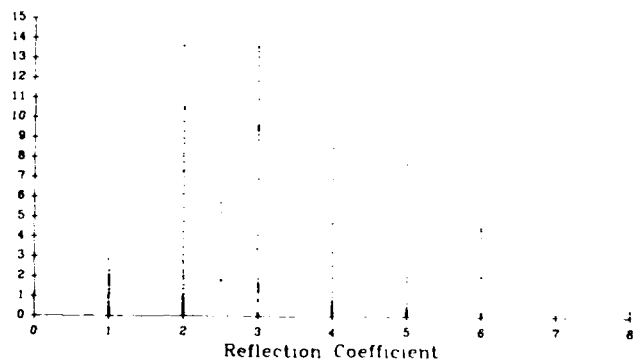


b. Visual signal reflections.

Figure 9. WCAX-TV GE reflections during iced and uniced conditions.



a. Aural signal reflections.



b. Visual signal reflections.

Figure 10. WCAX-TV GE reflections and estimated antenna ice accretions.

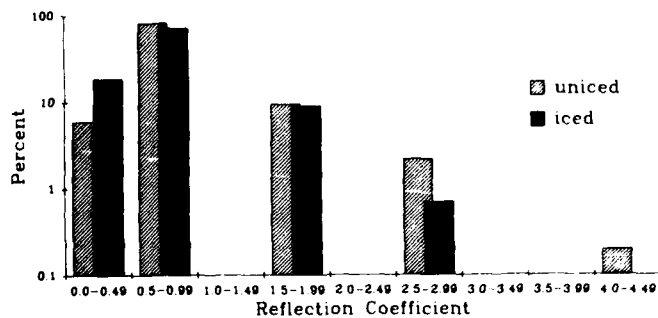


Figure 11. WCAX-TV composite reflections during iced and uniced conditions.

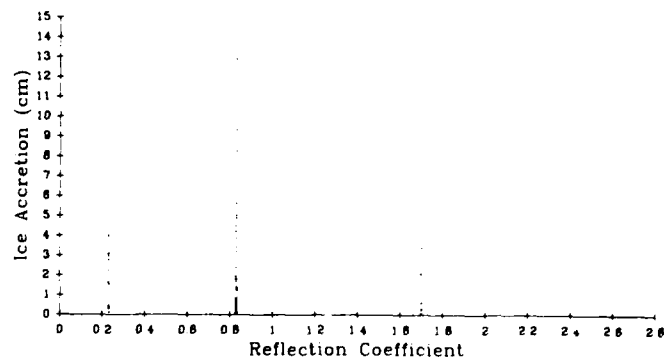


Figure 12. WCAX-TV composite reflections and estimated antenna ice accretions.

by ice than the larger, open WCAX-TV helix. As a result, the correlations may be more a function of ice amount and less a function of ice location on the antenna.

Other factors, especially those relating to the methods used to simulate antenna icing with the Rosemount ice detectors, may be producing the overall low and negative correlations, the low chi-

squares and the reversed amplitude means. Antenna ice may not be accreting at rates suggested by the Rosemount ice detector. That is, the ice detector may not be an effective emulator of antenna ice accretion, even when located in close proximity to the antenna. The ice detector may not be responding linearly to actual icing rates, especially the higher rates when the detector may be saturat-

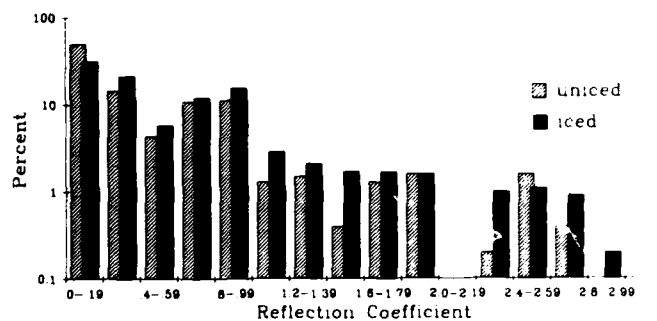


Figure 13. WHOM-FM reflections during iced and uniced conditions.

ing (Tucker and Howe 1984). However, curiously, the greatest correlation problems occur on Mount Mansfield where detector saturation should not be a problem. Also, antenna reflections may be more strongly caused by ice properties other than thickness, such as density, liquid water content and location on the antenna. For example, engineers at WHOM-FM have witnessed very high reflections when rime ice becomes water-saturated during thaws or freezing rains. In addition, ice may not necessarily mechanically release from the antenna when temperatures warm above freezing, and sublimation, solar radiation and winds were not accounted for.

CONCLUSIONS

Engineers and transmitter operators contacted for this study, as well as the National Association of Broadcasters (NAB 1985), stated that icing increases antenna reflections, degrades signal quality and endangers transmission equipment electrically. Unfortunately relationships between icing as recorded by Rosemount ice detectors adjacent to antennas and antenna reflections measured by broadcasters on Mount Mansfield and Mount Washington do not support these observations.

Several factors may be responsible for the inconsistent and unexpected results in this study. First, the Mount Washington icing record suffered may interruptions in its continuity. Though Observatory personnel intended that the detector be deactivated only during ice-free conditions, light icing conditions that could have influenced antenna reflections may have been missed. Second, the seven methods of simulating antenna ice accretion from Rosemount ice detector cycling may be un-

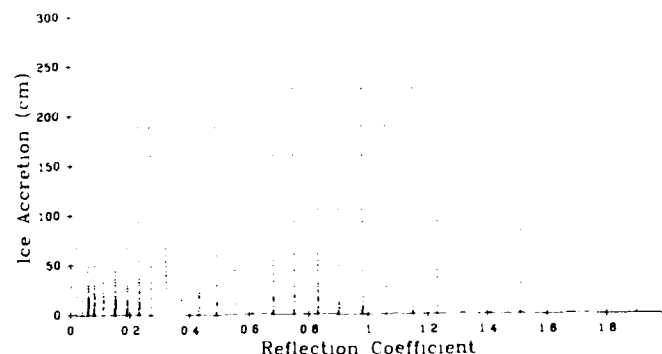


Figure 14. WHOM-FM reflections and estimated antenna ice accretions.

suitable and could be a factor in producing the inconsistent correlations. Therefore, the Rosemount ice detectors may not adequately represent ice accretion on antenna radiating surfaces. Factors that could not be measured, such as ice quality, ice location, antenna tuning and some weather variables, may be causing problems.

The relationships between ice and reflections found in this study indicate that reflection measurements are not adequate surrogates for ice measurements as measured by adjacent Rosemount ice detectors. However, since antenna icing and its effects are apparently serious broadcast problems, they deserve closer scrutiny and perhaps real-time analysis during an icing event. Ice thickness, quality and location on the antenna surface should be measured directly, and finely calibrated, sensitive VSWR meters should be used for reflection measurements. Dedicated measurements on a variety of antennas at different frequencies could provide a far more comprehensive understanding of the icing-antenna reflection phenomenon.

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