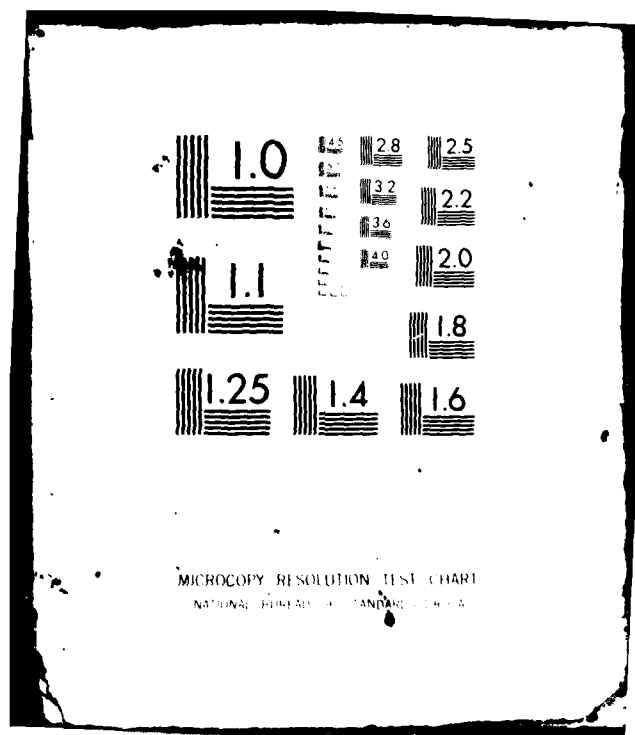


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EFFECT OF HAIL, SNOW, AND MELTING HYDROMETEORS
ON MILLIMETER RADIO WAVES

JULY 1981

By
Herbert K. Kobayashi

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US Army Electronics Research and Development Command

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ASL-TR-0092
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- Page 18 Figure 4, the numbers on the RAINDROP AND MELTED SNOWFLAKE
DIAMETER D(mm) should be corrected to read: 0.5, 1.0, 1.5,
2.0, 2.5, 3.0, 3.5, 4.0
- Page 19 Figure 6, the numbers on the RAINDROP DIAMETER(mm) should be
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report is a short survey intended to present the effect of solid and melting hydrometeors on millimeter radio waves. Hail and sleet were found to be more amenable to theoretical calculation and laboratory experimentation than snow because of their simpler approximations of particle shape and dielectric constant. However, field measurements on hail and sleet are scarce in comparison to snow. The most pressing need was found to be the gathering of reliable field data on the morphology and size distribution of hydrometeor		

20. ABSTRACT (cont)

particles, particularly those in a melting state where the effect on millimeter waves may exceed that of rain. These data are needed to more closely relate experimental measurement to theoretical calculation.

PREFACE

The author gratefully acknowledges the aid of Dr. Donald E. Snider of the US Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico; Mr. William B. Grant of the Institute for Telecommunication Sciences, Department of Commerce, Boulder, Colorado; and Ms. Vicky Schneller and the staff of the ITS/NOAA/NBS Library, Boulder, Colorado.

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INTRODUCTION

Recent reviews on the atmospheric effect on millimeter waves,¹⁻³ including one review by the author, have reported that the literature on nonliquid hydrometeors was very scarce. However, a more thorough search during the past year has uncovered several dozen articles yielding useful quantitative data. Unlike rain, attenuation and scatter by solid and melting hydrometeors have not been reviewed to any extent although Ryde in his classic World War II report on attenuation of millimeter waves⁴ allotted hail as much discussion as rain, fog, and clouds. As early as 1955, Robinson⁵ wrote: "... moist snow produced attenuation two and a half times greater than rain of similar precipitation rate." Some reasons for this apparent neglect may be:

a. Rain is a more frequently encountered hydrometeor and has overshadowed discussion on other forms of precipitation.

b. As in rain propagation, the computer modeling needed to compare experimental data with theoretical predictions is based on meager information, particularly for melting hydrometeors.

c. Unlike clear-air and rain experiments, field measurements must be done opportunistically on short-lived phenomena during seasonal conditions usually uncomfortable for experimenters.

A computerized author/title/subject search of major data bases across the nation by the Boulder Laboratories library staff (Department of Commerce, Boulder, Colorado) yielded about 50 papers linking millimeter waves with nonliquid hydrometeors. Many of these papers featured rain as the topic of importance. For the most part, the papers fell into three categories:

a. Experimental or measured attenuation, usually with reference to theoretical calculations.

¹D. M. Brown and M. B. Wells, 1978, A Literature Review of Millimeter and Submillimeter Radiation Absorption and Scatter in the Atmosphere, Final Report, ARBRL-CR-00382, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, AD A062375

²S. M. Kulpa and E. A. Brown, 1979, Near-Millimeter Wave Technology Base Study: Volume I - Propagation and Target/Background Characteristics, Special Report, HDL-SR-79-8, Harry Diamond Laboratories, Adelphi, MD

³H. K. Kobayashi, 1980, Atmospheric Effects on Millimeter Radio Waves, ASL-TR-0049, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, AD A081414

⁴J. W. Ryde and D. Ryde, 1945, Attenuation of Centimetre and Millimetre Waves by Rain, Hail, Fogs and Clouds, Report 8670, General Electric Research Laboratories, Wembley, England

⁵N. P. Robinson, 1955, "Measurements of the Effect of Rain, Snow and Fogs on 8.6 mm Radar Echoes," Proceedings IEEE, London, 203B:709

b. Theoretical or calculated attenuation and backscattering, often with reference to field measured backscattering.

c. Laboratory measurements of attenuation and backscattering with reference to theoretical calculations.

This report is presented in the sequence above. Since the decision as to whether a paper is experimental or theoretical is an arbitrary one, there is some overlap in the first two categories. There is a tendency for attenuation to be associated with one-way, point-to-point communication needs and for scatter, especially backscatter, to interest radar specialists.

EXPERIMENTAL OR MEASURED ATTENUATION

Research papers on attenuation fall into two categories:

a. Sufficient data taken to insure a graph of plotted points versus precipitation rate normally expressed as millimeters per hour equivalent rain rate.⁵⁻¹⁰

b. Only single values given for the occurrence of unusual weather situations.

The first category is listed in table 1 with attendant field data shown as average curves in figure 1. Snow ranging from dry to melting condition predominates, possibly because, like rain, snow is a long-lived phenomenon and an easy hydrometeor to identify. In a recent review, Kulpa and Brown found no experimental data on hail.²

⁵N. P. Robinson, 1955, "Measurements of the Effect of Rain, Snow and Fogs on 8.6 mm Radar Echoes," Proceedings IEEE, London, 203B:709

⁶Yu. S. Babkin et al, 1970, "Attenuation of Radiation at a Wavelength of 0.96 mm in Snow," Radio Engineering and Electronic Physics, 15:2171

⁷A. Nishitsuji, 1971, "Method of Calculation of Radio-Wave Attenuation in Snowfall," Electronics and Communications in Japan, 54-B:74

⁸T. Oomori and S. Aoyagi, 1971, "A Presumptive Formula for Snowfall Attenuation of Radio Waves," Electronics and Communications in Japan, 54-B:34

⁹V. G. Malinkin, A. V. Sokolov, and Ye. V. Sukhonin, 1976, "Attenuation of Signal at the Wavelength $\lambda = 8.6$ mm in Hydrometeors," Radio Engineering and Electronic Physics, 21:1

¹⁰W. W. Richard, J. E. Kammerer, and R. G. Reitz, 1977, "140-GHz Attenuation and Optical Visibility Measurements of Fog, Rain and Snow," Memorandum Report, ARBRL-MR-2800, Ballistics Research Laboratories, Aberdeen Proving Ground, MD

²S. M. Kulpa and E. A. Brown, 1979, Near-Millimeter Wave Technology Base Study: Volume I - Propagation and Target/Background Characteristics, Special Report, HDL-SR-79-8, Harry Diamond Laboratories, Adelphi, MD

TABLE 1. SNOWFALL ATTENUATION EXPERIMENTS AT MILLIMETER WAVELENGTHS

Reference Number	Year	Author(s)	Frequency (GHz)	Path Length (km)	Location	Comments
5	1955	Robinson, W.	35	15.3	Not stated (So. England?)	Dry and wet snow effect estimated
6	1970	Babkin, Y., et al	312.5	0.680	"Middle zone" of European USSR	Snowfall rate characterized
7	1971	Nishitsuji, A.	15, 35, 50	12.4	Sapporo, Japan	Wet, moist, and watery snow
8	1971	Omori, T., et al	11, 15, 24, 48*	8.9	Sapporo, Japan	Snowfall rate
9	1976	Malinkin, V., et al	35	5.6	Moscow, USSR	Dry snow
10	1977	Richard, W., et al	140	0.725	Not stated (Maryland, USA?)	Large, moist snowflakes

*Simultaneous radio propagation on all frequencies along the same path

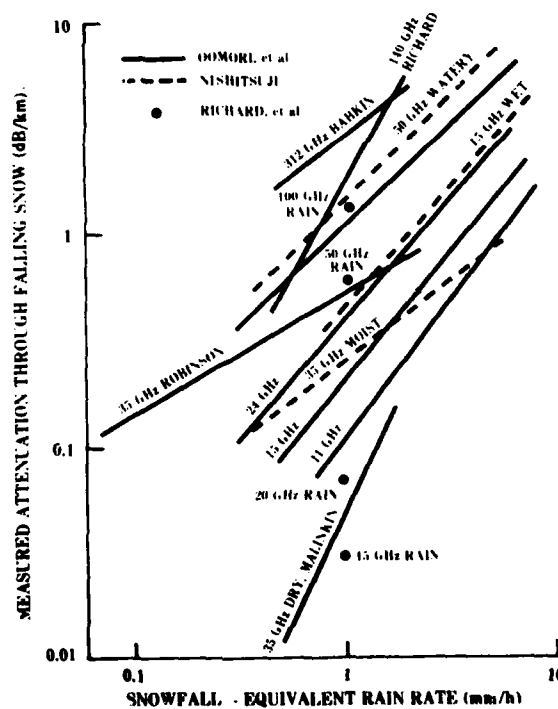


Figure 1. Measured attenuation through falling snow (further details in table 1).

Oomori and Aoyagi's comprehensive experiment⁸ merits initial discussion because it entailed simultaneous frequency measurements along the same 8.9 km path, thus enabling 11, 15, 24, and 48 GHz attenuation to be assessed for the same meteorological conditions. Their data are statistically reliable for indicating trends between 10 and 50 GHz because probability distributions for attenuation and precipitation rates, averaged over short intervals, were gathered during an entire winter season. First, there is a tendency for attenuation to increase with frequency and snowfall rate.

Asari verified this tendency for the same frequencies in his theoretical paper on wet snowfall.¹¹ Next attenuation at the precipitation rate of 1 mm/h is consistently greater than for rain (shown as dots in figure 1) at any given frequency. Richard¹⁰ reported this tendency for six frequencies, and Kulpa attributed the high attenuation to "... the large, more irregular shape of the snow precipitation and the fact that higher concentrations exist for the snow due to the low fall velocities."² Unfortunately, Oomori gave no details on the physical characteristics of snow. These characteristics determine the "statistical variations and qualities of the snow and precipitation."⁶

Nishitsuji⁷ was more conventional than Oomori in his comparison of measured and calculated attenuation at 15, 35, and 50 GHz. Six of the eight pages of his paper were devoted to transforming field snowflake measurements into data on the attenuation cross section and size distribution of snowflakes, which in turn are needed for calculated attenuation. Snow was placed into dry, moist, wet, and watery categories, each with five parameters, including temperature and density. As seen in figure 1, moist, wet, and watery conditions prevailed during the field measurements. Calculated and measured values agreed well according to Nishitsuji, and the trend toward greater attenuation seen in Oomori's work was also present. A comparison of the 15 and 35 GHz curves reveals that water content also contributes to greater attenuation.

⁸T. Oomori and S. Aoyagi, 1971, "A Presumptive Formula for Snowfall Attenuation of Radio Waves," Electronics and Communications in Japan, 54-B:34

¹¹E. Asari, 1974, "Attenuation of Microwaves in Moist or Wet Snowfall," Electronics and Communications in Japan, 57-B:58

¹⁰W. W. Richard, J. E. Kammerer, and R. G. Reitz, 1977, "140-GHz Attenuation and Optical Visibility Measurements of Fog, Rain, and Snow," Memorandum Report, ARBRL-MR-2800, Ballistics Research Laboratories, Aberdeen Proving Ground, MD

²S. M. Kulpa and E. A. Brown, 1979, Near-Millimeter Wave Technology Base Study: Volume I - Propagation and Target/Background Characteristics, Special Report, HDL-SR-79-8, Harry Diamond Laboratories, Adelphi, MD

⁷A. Nishitsuji, 1971, "Method of Calculation of Radio-Wave Attenuation in Snowfall," Electronics and Communications in Japan, 54-B:74

The remaining curves in figure 1 represent the data of four groups, each working at single frequencies.^{1 4 5 10} Apparently in all cases, the only snow characteristic quantitatively measured was snowfall intensity in equivalent rain rate (millimeters per hour).

Robinson⁵ and Malinkin et al⁹ worked at 35 GHz. The former reported 2.5 times greater attenuation in wet snow than attenuation caused by rain at the same precipitation rate. On the other hand, Malinkin experienced 2.5 times less attenuation for dry snow. Rain data from Richard et al,¹⁰ also reproduced in Kulpa and Brown,² are plotted as dots in figure 1 for selected frequencies. These data averaged from several sources by Richard correspond within one order of magnitude at a snowfall intensity of 1 mm/h. Robinson and Malinkin also agree with Nishitsuji⁷ and Lammers¹² at 35 GHz for wet and dry snow, respectively.

Richard et al¹⁰ and Babkin⁶ experienced the highest attenuations according to figure 1. These attenuation rates would be expected from the foregoing discussion. Richard's measurements of 140 GHz attenuation made through large, moist snowflakes reached a maximum of 5.5 dB/km at the snowfall rate of 1.2 mm/h. Generally, attenuation was three times greater than for rain at the same equivalent rain rate, and three to five times greater than for five other cited investigations in millimeter-wave propagation. Babkin did not qualitatively describe snow during his 312 GHz experiment. However, dry conditions are implied since dry, not wet, snow is theoretically discussed; and maximum

⁵N. P. Robinson, 1955, "Measurements of the Effect of Rain, Snow, and Fogs on 8.6 mm Radar Echoes," Proceedings IEEE, London, 203B:709

⁶Yu. S. Babkin et al, 1970, "Attenuation of Radiation at a Wavelength of 0.96 mm in Snow," Radio Engineering and Electronic Physics, 15:2171

⁹V. G. Malinkin, A. V. Sokolov, and Ye. V. Sukhonin, 1976, "Attenuation of Signal at the Wavelength $\lambda = 8.6$ mm in Hydrometeors," Radio Engineering and Electronic Physics, 21:1

¹⁰W. W. Richard, J. E. Kammerer, and R. G. Reitz, 1977, "140-GHz Attenuation and Optical Visibility Measurements of Fog, Rain, and Snow," Memorandum Report, ARBRL-MR-2800, Ballistics Research Laboratories, Aberdeen Proving Ground, MD

²S. M. Kulpa and E. A. Brown, 1979, Near-Millimeter Wave Technology Base Study: Volume I - Propagation and Target/Background Characteristics, Special Report, HDL-SR-79-8, Harry Diamond Laboratories, Adelphi, MD

⁷A. Nishitsuji, 1971, "Method of Calculation of Radio-Wave Attenuation in Snowfall," Electronics and Communications in Japan, 54-B:74

¹²U. Lammers, 1967, "The Attenuation of mm-Waves by Meteorological Precipitation," NTZ Communications Journal, 6:230

attenuations were only 30 to 40 percent greater than for previously reported rain measurements. Dry snow would explain the fact that his attenuation curve is only slightly higher than Richard's curve for wet snow at 140 GHz.

Single values for snow and sleet (partly frozen rain) are sometimes encountered in the literature, often in conjunction with rain experiments. Some examples of these values at millimeter wavelengths are:

- a. Weibel¹³ - 4 dB additional fade at 90 GHz during heavy, wet snowfall.
- b. Tattersall¹⁴ - 34 dB fade at 37 GHz for 11, 22, and 37 GHz during severe, wet storm.
- c. Misme¹⁵ - 15 to 25 dB loss for several minutes on vertically and horizontally polarized channels at 11 GHz during severe sleeting.
- d. Watson¹⁶ - 2 dB/km co-polar and cross-polar fades at 11 GHz during rain, sleet, and snow conditions.

Watson also wrote a review on the lower millimeter wavelengths¹⁷ in which he reported briefly on snow and sleet, citing several papers in this area of research.

A summary of measured attenuation shows that snow, notably in its melting state, is the only nonliquid hydrometeor with any substantial amount of reported data. Open literature tends to show that snow attenuation increases with frequency, snowfall rate, and snowflake liquid water content.

¹³G. E. Weibel and H. O. Dressel, 1967, "Propagation Studies in Millimeter-Wave Link Systems," Proceedings IEEE, 55:497

¹⁴R. L. O. Tattersall, 1975, "Snow Fading on 1 March 1974 on Microwave Links in the Mendlesham Propagation Experiment," Electronics Letters, 11:603

¹⁵P. Misme, 1979, "Un Affaiblissement Exceptionnel dû à la Neige Mouillée," (An Exceptional Attenuation due to Sleet), Annales des Telecommunication, 34:291

¹⁶P. A. Watson, 1973, "Attenuation and Cross-Polarization Measurements at 11 GHz," IEEE Transactions Communications, COM-21:325

¹⁷P. A. Watson, 1976, "Survey of Measurements of Attenuation by Rain and Other Hydrometeors," Proceedings IEEE, London, 123:863

THEORETICAL CALCULATION AND MEASURED BACKSCATTER

Theoretical calculations incorporating hydrometeor field data are necessary for interpreting experimental field measurements. From Ryde and Ryde in 1945¹ to Evans and Holt in 1980,¹⁰ solid and melting precipitation have been considered along with rain. But the irregular shape and variable index of refraction of these particles make comparisons between measured and calculated values difficult. There are no generally accepted field data for these particles such as the Laws-Parson and Marshall-Palmer raindrop size distributions.^{19 20} For convenience, this section of the report is separated into discussions of hail and snow. Hail and sleet are often modeled as spheroids with an ice or ice and water dielectric constant. Snow modeling is a more difficult task, with dry snow conditions producing the best agreement between theory and experiment.

Hail

In view of the lack of experimental data on radio propagation through hail,² the validity of representing hailstones as concentric spheres or prolate

¹J. W. Ryde and D. Ryde, 1945, Attenuation of Centimetre and Millimetre Waves by Rain, Hail, Fog and Clouds, Report 8670, General Electric Research Laboratories, Wembley, England

¹⁰B. G. Evans and A. R. Holt, 1980, "A Review of Theoretical Prediction Techniques of Transmission Parameters for Slant-Path, Earth-Space Communications," AGARD Conference Proceedings, AGARD-CP-284:3-1, London, UK, 12-16 May 1980

¹⁹J. O. Laws and D. A. Parsons, 1943, "The Relation of Raindrop-Size to Intensity," Transactions, American Geophysical Union, 24:452

²⁰J. S. Marshall and W. McK. Palmer, 1948, "The Distribution of Raindrops with Size," Journal of Meteorology, 5:165

²S. M. Kulpa and E. A. Brown, 1979, Near-Millimeter Wave Technology Base Study: Volume I - Propagation and Target/Background Characteristics, Special Report, HDL-SR-79-8, Harry Diamond Laboratories, Adelphi, MD

spheroids²¹⁻²⁷ needs to be compared to direct field observations.²⁸⁻²⁹ Barge and Isaac²⁸ analyzed nearly 2000 Alberta specimens and found that about 70 percent were oblate and prolate ellipsoids and cones. Wide variability in their data was apparent when 74 percent were cones in one storm and 72 percent were oblate spheroids in another storm only 8 days later. Matson and Huggins²⁹ photographed hailstones in several Colorado storms and classified the majority as oblate spheroids and 16 percent as cones. Variability in maximum dimension and size distribution from event to event was also reported.

Literature contains several examples where questions have been raised regarding single-model backscatter calculations proposed as a way of separating rain from hail. The following recent example illustrates the need for field data on hailstone shape to clarify this long-standing problem. According to Seliga and Bringi,²⁷ large, dry hail modeled as an oblate spheroid would yield a differential backscatter (that is, the ratio of vertical to horizontal polarization) which is negative, as opposed to a positive value for rain. Aydin and Hizal's calculations with cones as well as oblate spheroids reveal that

²¹E. Asari, 1969, "Analysis and Algorithm for Computing the Forward Scattering Cross Section of a Dielectric Sphere," Electronics and Communications in Japan, 52-B:43

²²M. T. Abshayev and V. I. Rozenberg, 1969, "Scatter and Attenuation of Radar Emission by Water-Surrounded Hailstones," Atmospheric and Oceanic Physics, 5:560

²³V. I. Rozenberg, 1970, "Scattering of Microwaves by Flaky Hailstones," Atmospheric and Oceanic Physics, 6:91

²⁴V. I. Rozenberg, 1970, "Diffraction and Scattering of Electromagnetic Waves by an Inhomogeneous Sphere," Izvestiya Vysshikh Uchebnykh Zavendenii, Radiofizika, 13:337

²⁵V. I. Rozenberg and R. M. Vorob'yev, 1971, "Scattering and Attenuation of 3.2-cm Microwaves by Inhomogeneous Hail Particles," Atmospheric and Oceanic Physics, 7:632

²⁶A. W. Dissanayake and P. A. Watson, 1977, "Forward Scatter and Cross-Polarization from Spheroidal Ice Particles," Electronics Letters, 13:140

²⁷T. A. Seliga and V. N. Bringi, 1978, "Differential Reflectivity and Differential Phase Shift: Applications in Radar Meteorology," Radio Science, 13:271

²⁸B. L. Barge and G. A. Isaac, 1973, "The Shape of Alberta Hailstones," Journal de Recherches Atmospheriques, 7:11

²⁹R. J. Matson and A. W. Huggins, 1980, "The Direct Measurement of the Sizes, Shapes and Kinematics of Falling Hailstones," Journal of the Atmospheric Sciences, 37:1107

under certain circumstances hail identification may become difficult and other polarization ratios may be needed for clarification.¹⁰

Hail size distributions obtained by Khorvani and Tliso¹¹ and Federer and Waldvogel¹² in mountainous regions of Europe were different from those of earlier workers. Khorvani concluded that a "logarithmically normal" distribution was a better fit than the gamma function and bimodal ones of his Russian colleagues. Federer's data appeared to have an exponential fit as shown in figure 2.

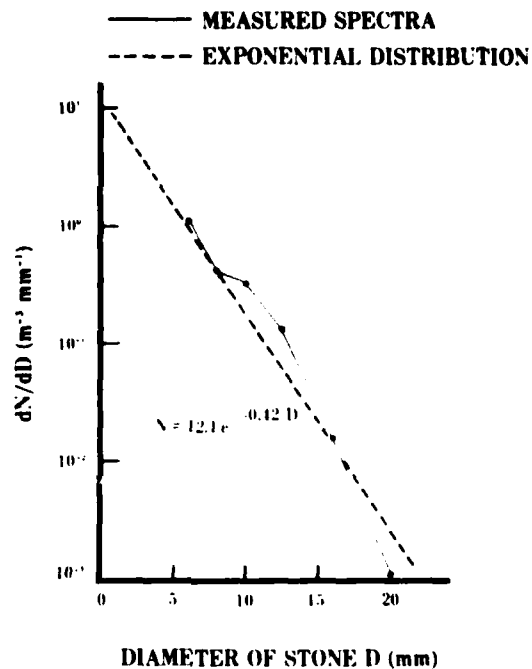


Figure 2. Mean hail distribution from Federer and Waldvogel, 1975, Journal of Applied Meteorology, 14:91. Hailstones defined as particles with $D \geq 5$ mm.

¹⁰K. Aydin and A. Hizal, 1979, "Back-Scattering from Melting Hail-Pellets," IEEE-URSI International Symposium, Antennas and Propagation, p 503, Seattle, WA

¹¹V. G. Khorvani and M. I. Tliso, 1974, "Size Distribution Function of Hailstones," Atmospheric and Oceanic Physics, 10:269

¹²B. Federer and A. Waldvogel, 1975, "Hail and Raindrop Size Distributions from a Swiss Multicell Storm," Journal of Applied Meteorology, 14:91

Snow

Although open literature does not contain experimental data on hail, it does contain experimental data on radio propagation through falling snow (discussed in preceding paragraphs of this report). But the complex shape of snowflakes and their ice-air-water composition make theoretical calculations more difficult than for hail and sleet. Richard et al.¹⁰ in a brief review of snow attenuation pointed out that calculations based on equivalent rain rate, particularly for melting snow, are usually lower than measured results. This statement implies that a poor comparison will occur even when a dry snowflake is modeled as a water sphere. This situation appears to be the case in Babkin's comparison with Mie theory calculations based on an "equivalent" water sphere.⁶

Lammers¹² assigned complex dielectric values to snow as an ice-air mixture (a very dry condition) and showed that the total cross section (which includes attenuation and scatter) for Mie calculations at 54 GHz is one order of magnitude smaller than for rain. He also calculated attenuation for dry snow and claimed agreement within one order of magnitude of field measurements. His calculations (figure 3) also appear to agree with other curves of figure 1 to the same order of magnitude.

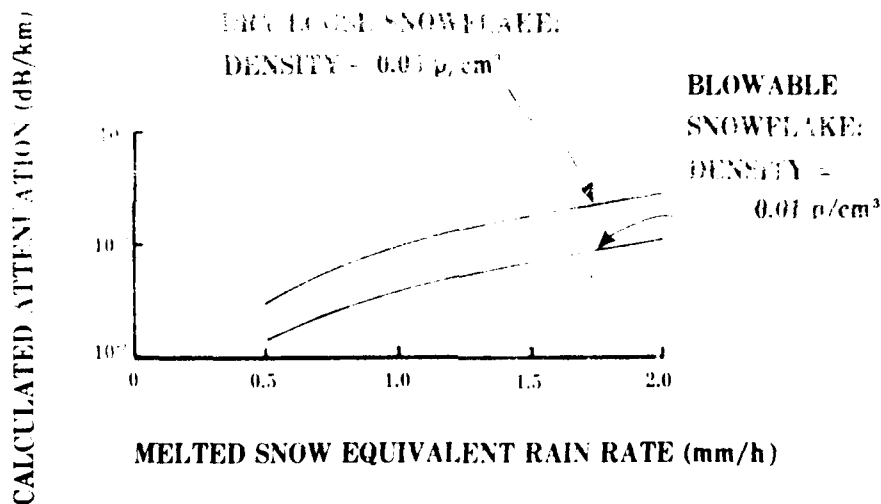


Figure 3. Calculated attenuation at 54 GHz from Lammers, 1967, NTZ Communications Journal, 6:230.

¹⁰W. W. Richard, J. E. Kammerer, and R. G. Reitz, 1977, "140-GHz Attenuation and Optical Visibility Measurements of Fog, Rain and Snow," Memorandum Report, ARBRL-MR-2800, Ballistics Research Laboratories, Aberdeen Proving Ground MD

⁶Yu. S. Babkin et al, 1970, "Attenuation of Radiation at a Wavelength of 0.96 mm in Snow," Radio Engineering and Electronic Physics, 15:2171

¹²U. Lammers, 1967, "The Attenuation of mm-Waves by Meteorological Precipitation," NTZ Communications Journal, 6:230

Size distribution of snowflakes and graupels (granular snow pellets) has been studied mainly by weather radar experimenters because of the importance of identifying and assessing the quantity of hydrometeor particles. The desired parameters are generally the radar reflectivity Z plotted against precipitation intensity or rate R .¹ Since comparison between rain and the snowfall equivalent rain rate is frequently made, the mass of the snowflake rather than its physical size is measured.² The technique often employed is to measure the diameter of the drop resulting from melting a snowflake on filter paper coated with a water-soluble dye such as gentian violet.³ A more elaborate method is to measure photographs of crystals reduced to spheres in heated silicone oil.⁴ The terminal velocity of snowflakes, needed to compute the mass-size distribution on a volume basis ($\text{millimeter}^{-1} \text{ m}^{-3}$), is usually taken from Langleben.⁵ Mogono⁶ stated that Langleben's fall velocities are applicable to small snowflakes only and that the velocities are related more to size and density than to mass.

Previous attempts to relate backscatter measurements to calculations based on snow size distributions have had mixed success. Imai et al.⁷ found that snowflake coalescence affected size distribution to such an extent that the Z - R coefficient changed by about a factor of 4 in a 2-h period. Gunn and Marshall⁸ reported that their distribution using Langleben's velocities

¹H. K. Kobayashi, 1980, Atmospheric Effects on Millimeter Radio Waves, ASL-TR-0049, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, AD A081414

²K. L. S. Gunn and J. S. Marshall, 1958, "The Distribution with Size of Aggregate Snowflakes," Journal of Meteorology, 15:452

³A. Nishitsuji, 1971, "Method of Calculation of Radio-Wave Attenuation in Snowfall," Electronics and Communications in Japan, 54-B:74

⁴T. Yagi, H. Uyeda, and H. Seino, 1979, "Size Distribution of Snowflakes and Graupel Particles Observed in Nagaoka, Niigata Prefecture," Journal of the Faculty of Science, Hokkaido University, Ser VII, 6:79

⁵I. Imai et al, 1955, "Radar Reflectivity of Falling Snow," Meteorology and Geophysics (Japan), 6:130

⁶M. Kajikawa, 1972, "Measurement of Falling Velocity of Individual Snow Crystals," Journal of the Meteorological Society of Japan, 50:577

⁷M. P. Langleben, 1954, "The Terminal Velocity of Snowflakes," Quarterly Journal of the Royal Meteorological Society, 80:174

⁸C. Magono, 1965, "Aerodynamic Studies of Falling Snowflakes," Journal of the Meteorological Society of Japan, 43:139

(figure 4) agreed with Imai's data and the Marshall-Palmer rain distribution²⁰ at low intensities of R (figures 5 and 6). A recent study by Yagi et al¹¹ compared well with the Gunn and Marshall distribution (figure 7). However, the authors clearly showed that the same reflectivity Z can be returned by two storms differing greatly in size and distribution of snowflake and graupel. On the basis of their findings, Yagi recommended restricting the usage of the Z-R relationship for snow to weather at a specific locale.

In a few papers, the morphology or physical state of snowflakes has been explicitly related to attenuation or scatter. A typical example was by Asari¹¹ who divided snow into six categories, from slightly moist to very wet, each with a particular dielectric constant at 11, 24, and 35 GHz. He then found the total cross section and compared attenuation with measured data at 11 and 35 GHz. Although no experimental confirmation was apparent, Asari's calculations for attenuation by particles of "equal nature and size" (figure 8) indicate that at 11 and 35 GHz a unique maximum is attained in each of the six snow categories.

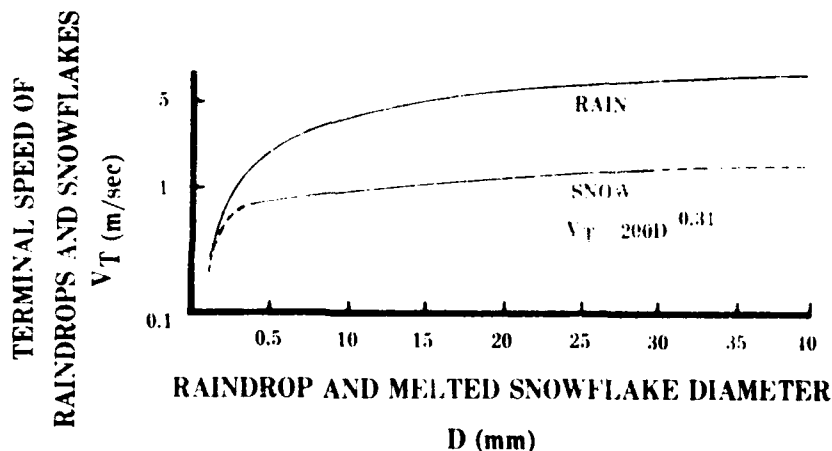


Figure 4. Terminal speeds of raindrops (from Gunn and Kinzer, 1949, Journal of Meteorology, 6:243) and snowflakes (from Langleben, 1954, Quarterly Journal of the Royal Meteorological Society, 80:174) as a function of diameter.

²⁰J. S. Marshall and W. McK. Palmer, 1948, "The Distribution of Raindrops with Size," Journal of Meteorology, 5:165

¹¹T. Yagi, H. Uyeda, and H. Seino, 1979, "Size Distribution of Snowflakes and Graupel Particles Observed in Nagaoka, Niigata Prefecture," Journal of the Faculty of Science, Hokkaido University, Ser VII, 6:79

¹¹E. Asari, 1974, "Attenuation of Microwaves in Moist or Wet Snowfall," Electronics and Communications in Japan, 57-B:58

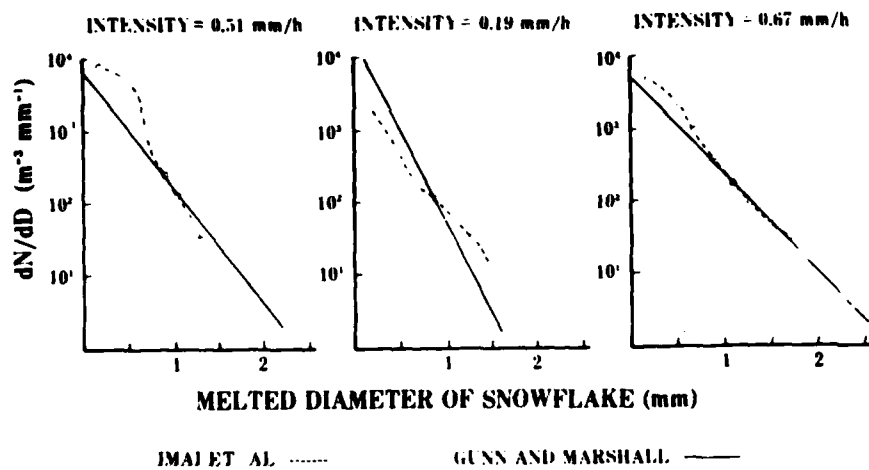


Figure 5. Three average size distributions for snow from Imai et al, Meteorology and Geophysics (Japan), 6:130 (dotted lines) and Gunn and Marshall, 1958, Journal of Meteorology, 15:452 (straight lines).

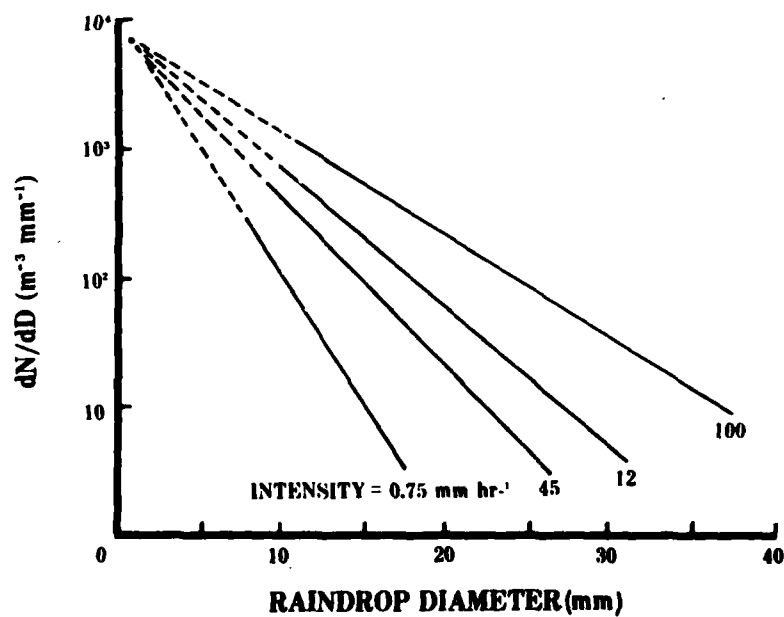


Figure 6. Marshall-Palmer (1948) average rain distributions for four intensities from Journal of Meteorology, 5:165.

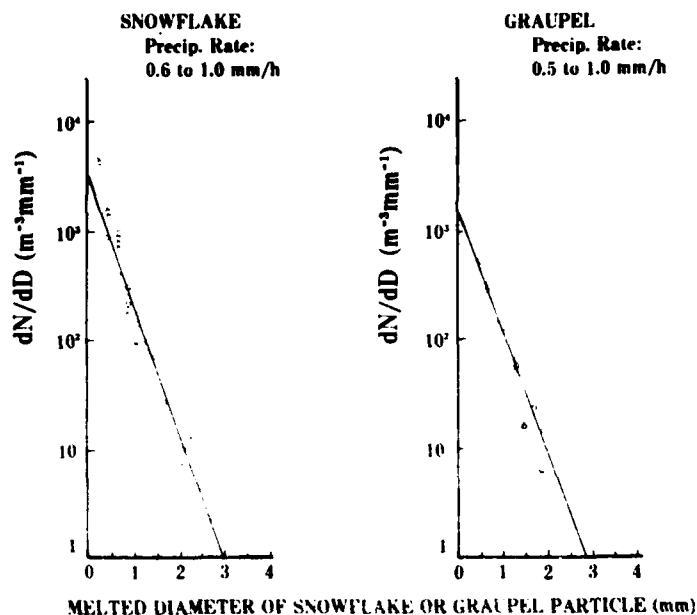


Figure 7. Size distribution for snowflakes and graupel particles from Yagi et al, 1979, Journal of the Faculty of Science, Hokkaido University, Ser VII, 6:79.

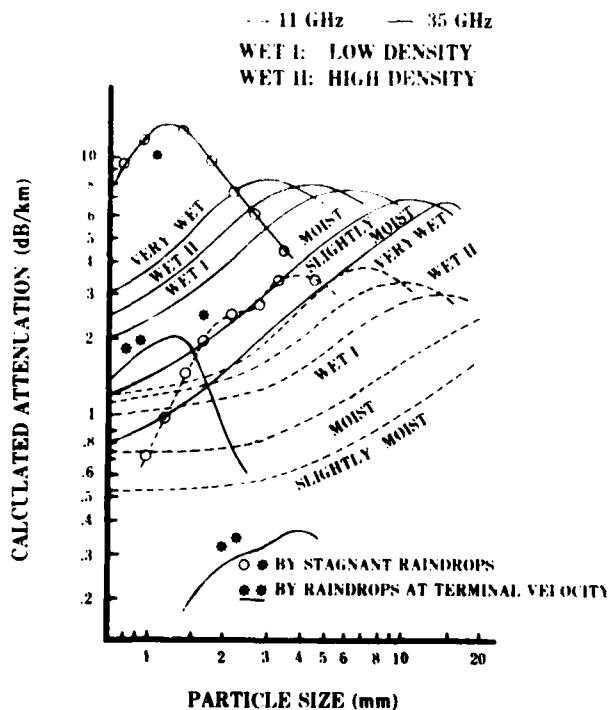


Figure 8. Calculated attenuation by various kinds of snow particles from Asari, Electronics and Communications in Japan, 57-8:58.

A summary of theoretical calculations, especially with respect to backscatter, shows that the effect of hail on millimeter waves is hampered by the lack of field measurements taken in concert with data on the morphology and distribution of hailstones. For snow, good agreement between experiment and theory is found for small, dry flakes represented as an ice and air spheroid. For larger, wetter flakes having the tendency to aggregate with size, no satisfactory model has been found in the literature, and calculated values based on spheroids show poorer correlation with experimental values.

LABORATORY MEASUREMENTS OF SINGLE PARTICLES

Attempts to predict attenuation and scatter from hydrometeors at millimeter wavelengths began with Ryde and Ryde¹ during World War II with solid and liquid particles (rain, hail, and fog). Later, Gunn and Marshall² and Marshall and Gunn³ extended Rydes' work to snow "...conveniently expressed in terms of the diameter of the water drop to which the snowflake would melt, assuming no break-up." It was soon realized that no one meteorological factor would suffice to link size distribution and synoptic condition. However, as late as 1970, Babkin et al⁴ assumed a spherical shape for snow and applied Gunn and Marshall's size distribution to Mie theory computations. Their results show poor comparison between measured and computed curves. Since Babkin's work at 312 GHz appears to be the only one available for snow at the high millimeter frequencies, his involved argument for introducing an "effective radii of spherical snow particles" should be examined with care. Thus it appears that problems are encountered in assuming simple shapes for hydrometeors, and therefore it would be very useful to obtain direct measurements of attenuation and scatter from particles of known configuration.

The need to collect data on the effect of hydrometeor particles under controlled laboratory conditions has resulted in a small body of papers from about

¹J. W. Ryde and D. Ryde, 1945, Attenuation of Centimetre and Millimetre Waves by Rain, Hail, Fogs, and Clouds, Report 8670, General Electric Research Laboratories, Wembley, England

²K. L. S. Gunn and J. S. Marshall, 1958, "The Distribution with Size of Aggregate Snowflakes," Journal of Meteorology, 15:452

³J. S. Marshall and K. L. S. Gunn, 1952, "Measurement of Snow Parameters by Radar," Journal of Meteorology, 9:322

⁴Yu. S. Babkin et al, 1970, "Attenuation of Radiation at a Wavelength of 0.96 mm in Snow," Radio Engineering and Electronic Physics, 15:2171

1952 to 1980.¹¹⁻¹⁷ All of these papers are measurements of single particles, the multiple-scattering interactions being intractable in experimentation as well as theory. They fall into two kinds of determinations:

- a. Backscatter matrix based on various techniques,¹¹⁻¹⁴ and
- b. Extinction cross section (attenuation plus scatter) based on a technique by Cullen and Kumar.¹⁵⁻¹⁶

Backscatter measurements were made by Labrum¹¹ in 1952 at 3 GHz on liquid spheres and melting rods and discs of approximately 0.1 wavelength. He confirmed the "bright band" backscatter phenomenon and polarization rotation from nonspherical scatterers long observed by radar operators. Nicholis¹² examined the 18 to 25 GHz range with rectangular frozen specimens of resonant wavelength and agreed with Labrum in detecting a backscatter maximum during melting at the lower wavelengths. In his comprehensive theoretical paper on scattering and absorption by hail modeled as melting ice spheres at 34.8 GHz, Oguchi¹³ also found a maximum during the melting process.

¹¹N. R. Labrum, 1952, "Some Experiments on Centimeter-Wavelength Scattering by Small Obstacles," Journal of Applied Physics, 23:1320

¹²N. R. Labrum, 1952, "The Scattering of Radio Waves by Meteorological Particles," Journal of Applied Physics, 23:1324

¹³J. Nicholis, 1965, "The Wavelength Dependence (between 18 to 25 Gc/s) of Back-Reflected Energy from Small Ice Particles during the Melting Process," Proceedings of the IEEE, 53:551

¹⁴L. E. Allan and G. C. McCormick, 1978, "Measurements of the Backscatter Matrix of Dielectric Spheroids," IEEE Transactions on Antennas and Propagation, AP-26:579

¹⁵L. E. Allan and G. C. McCormick, 1980, "Measurements of the Backscatter Matrix of Dielectric Bodies," IEEE Transactions on Antennas and Propagation, AP-28:166

¹⁶A. L. Cullen and A. Kumar, 1970, "The Absolute Determination of Extinction Cross-Sections by the Use of an Open Resonator," Proceedings of the Royal Society of London, Sect A, 315:217

¹⁷J. R. Gerhardt et al, 1961, "Experimental Determinations of the Backscattering Cross-Section of Water Drops and of Wet and Dry Ice Spheres at 3.2 Centimeters," Journal of Meteorology, 18:340

¹⁸D. L. Bryant and L. J. Auchterlonie, 1978, "Measurement of the Extinction Cross-Sections of Dry and Wet Ice Spheres at 35 GHz," Electronics Letters, 15:52

¹⁹T. Oguchi, 1966, "Scattering and Absorption of a Millimeter Wave Due to Rain and Melting Hailstones," Journal of the Radio Research Laboratories (Japan), 13:141

Recently, Allan and McCormick,¹¹ with measurements at 2.86 GHz, related scattering coefficients in the horizontal and vertical planes to the aspect angle (that is, the angle between the symmetry axis and the propagation direction) for dielectric spheroids 0.242 to 1.22 wavelengths maximum dimension simulating ice (dielectric constant $\epsilon = 3.18$). Some agreement with theory and measurement by others is claimed by the authors, although conspicuous differences were seen in the backscatter cross section for spheroids in the Rayleigh region.

Extinction cross section by Cullen and Kumar's method¹² involves a simple, straightforward measurement of the change in Q-factor due to an obstacle placed in an open resonator. The obstacle must have reflective symmetry perpendicular to the incident wave, and thus far only spheroids have been studied with this method. Experiments by Gerhardt et al.¹³ at 9.4 GHz with water drops and wet and dry ice spheres 0.5- to 11.0-wavelength diameter were in general agreement with Mie theory except for the melting values. Bryant and Auchterlonie¹⁴ also encountered difficulty in preparing specimens and interpreting results with ice spheres. Their problem was in qualitatively assessing the degree of melt when replicating their readings at the wavelength of only 8.6 mm (35 GHz).

A summary of laboratory measurements of single particles shows that mixed results have been reported for ice, melting ice, and synthetic dielectric particles of spherical to rectangular shapes of resonant size between 2.86 and 35 GHz. A serious technical problem is assessing the degree of melt for ice-water specimens in replicating data. This problem will become acute at higher millimeter frequencies with their smaller resonant particles.

¹¹L. E. Allan and G. C. McCormick, 1978, "Measurements of the Backscatter Matrix of Dielectric Spheroids," IEEE Transactions on Antennas and Propagation, AP-26:579

¹²L. E. Allan and G. C. McCormick, 1980, "Measurements of the Backscatter Matrix of Dielectric Bodies," IEEE Transactions on Antennas and Propagation, AP-28:166

¹³A. L. Cullen and A. Kumar, 1970, "The Absolute Determination of Extinction Cross-Sections by the Use of an Open Resonator," Proceedings of the Royal Society of London, Sect A, 315:217

¹⁴J. R. Gerhardt et al, 1961, "Experimental Determinations of the Back-scattering Cross-Section of Water Drops and of Wet and Dry Ice Spheres at 3.2 Centimeters," Journal of Meteorology, 18:340

¹⁵D. L. Bryant and L. J. Auchterlonie, 1978, "Measurement of the Extinction Cross-Sections of Dry and Wet Ice Spheres at 35 GHz," Electronics Letters, 15:52

CONCLUSIONS

Snow, notably in its melting state, is the only nonliquid hydrometeor with any substantial amount of reported data at millimeter wavelengths. The open literature tends to show that snow attenuation increases with frequency, equivalent rain rate, and snowflake liquid water content.

Hail and sleet are more amenable to theoretical calculation and laboratory experimentation than snow because of their simpler approximations of particle shape and dielectric constant. On the other hand, field measurements on hail and sleet are comparatively scarce due to their transient nature.

Apparently the lack of reliable field data on hydrometeors other than rain has made comparison between experimental measurement and theoretical calculation difficult.

RECOMMENDATIONS

The most pressing need is for field data on characteristics of hydrometeor particles taken with the usual equivalent rain rate. Several references in this review have pointed out what characteristics are important for theoretical calculations. As with rain,^{19 20 21} data for other hydrometeors are

¹⁹J. O. Laws and D. A. Parsons, 1943, "The Relation of Raindrop-Size to Intensity," Transactions, American Geophysical Union, 24:452

²⁰J. S. Marshall and W. McK. Palmer, 1948, "The Distribution of Raindrops with Size," Journal of Meteorology, 5:165

²¹R. Gunn and G. D. Kinzer, 1949, "The Terminal Velocity of Fall for Water Droplets in Stagnant Air," Journal of Meteorology, 6:243

still valuable even if not taken in conjunction with radio propagation measurements.^{20 21 22 23 24 25 26 27}

Melting snow has been shown to affect millimeter waves to the same extent as rain and should be given priority over less effective hydrometeors of lower liquid water content. Comparative treatment of melting snow and rain during the same storm^{20 21} is especially valuable because the effect of rain is relatively well understood up to 140 GHz.²²

²⁰B. L. Barge and G. A. Isaac, 1973, "The Shape of Alberta Hailstones," Journal de Recherches Atmosphériques, 7:11

²¹R. J. Matson and A. W. Huggins, 1980, "The Direct Measurement of the Sizes, Shapes and Kinematics of Falling Hailstones," Journal of the Atmospheric Sciences, 37:1107

²²V. G. Khorguani and M. I. Tlisov, 1974, "Size Distribution Function of Hailstones," Atmospheric and Oceanic Physics, 10:269

²³B. Federer and A. Waldvogel, 1975, "Hail and Raindrop Size Distributions from a Swiss Multicell Storm," Journal of Applied Meteorology, 14:91

²⁴K. L. S. Gunn and J. S. Marshall, 1958, "The Distribution with Size of Aggregate Snowflakes," Journal of Meteorology, 15:452

²⁵T. Yagi, H. Uyeda, and H. Seino, 1979, "Size Distribution of Snowflakes and Graupel Particles Observed in Nagats, Niigata Prefecture," Journal of the Faculty of Science, Hokkaido University, Ser VII, 6:79

²⁶M. Kajikawa, 1972, "Measurement of Falling Velocity of Individual Snow Crystals," Journal of the Meteorological Society of Japan, 50:577

²⁷M. P. Langleben, 1954, "The Terminal Velocity of Snowflakes," Quarterly Journal of the Royal Meteorological Society, 80:174

²⁸T. Ohtake, 1969, "Observations of Size Distributions of Hydrometeors Through the Melting Layer," Journal of the Atmospheric Sciences, 36:546

²⁹T. Ohtake, 1970, "Factors Affecting the Size Distribution of Raindrops and Snowflakes," Journal of the Atmospheric Sciences, 27:804

³⁰S. Okamura and A. Sonohara, 1977, "Atmospheric Attenuation by Rain at 140 GHz," Electronics and Communications in Japan, 60-B:94

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