ESTIMATING SNOWFALL RATES COMPARING RADAR AND AIRBORNE MEASUREMENTS

BY: YARICE RODRIGUEZ
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Introduction

Snowfall is a form of precipitation that can cause hazardous weather conditions. In a storm various types of precipitation form. The most typical forms of precipitation are rain, fog, snow and hail. Many other types exist as well.

This research will focus on snowfall precipitation. It is part of an international effort determining snowfall rates over the Swiss Alps. This project comprises two important atmospheric science fields: radar meteorology and cloud physics. The projects specific objective was to develop a method to estimate snowfall rates derived from “S-Pol” radar measurements using aircraft measurements hence providing people with more information about potential flood hazards and, water resource problems and also aid in agricultural planning by using polarimetric capabilities.

Comparing aircraft and “S-Pol” radar data sets was of prime interest. The radar is the perfect instrument for measuring snowfall rates over rough terrain, but has never been used before due to the complexity of snow. The aircraft can provide the needed information about the complexity of the snow. Therefore, it is important to validate a matching program developed by Dr. William Cooper (National Center for Atmospheric Research) and Dr. Sabine Goeke (Advanced Study Program), which correlate points between aircraft flight tracks and radar scans. Such matching was realized for the first time among the scientific community at NCAR.

Immediate Problem

The area under observation was the Swiss Alps, which has rough terrain that makes it difficult to measure snow on the ground. The Alps is an area susceptible to treacherous snowstorms. After these snowstorms the snow melts and produces floods that can wipe existing villages away. Understanding the rate of snow that reach the earth through calculating particle density ($\rho$) can provide valuable information on the amount of water that is in snow.

MAP Background

In 1999 as part of the Mesoscale Alpine Programme (MAP) (Contributing Authors, 1998) in northern Italy, data on snowfall rates of the southern Swiss Alps was collected. MAP proposed to study cloud and precipitation processes over rough orographic terrain. An international effort of over 12 countries in Europe and Canada from over 25 institutions began MAP. It started in the early 1990’s. American proposal for participation did not occur till relatively late in the projects design, in 1995.
American involvement was motivated by the possibility of solving some problems of orographic meteorology while utilizing European contributions in project infrastructure and science know-how. Years of preparation were required prior to the actual field experiment. For example, MAP encompassed an intensive two-year modeling phase, numerical experimentation, inter-comparison effort between international modeling groups, and attempts to prepare and optimize the field phase approach.

MAP’s critical pre-planning proved successful when the following data collection platforms were made available by the United States for data collection:
1. The NCAR Electra (scientific aircraft with Knollenberg particle measuring system (PMS) probes mounted onto the wings) and
2. The transportable NCAR “S-Pol” (a polarimetric Doppler radar for dual Doppler and microphysical studies).

Another instrument belonging to the Swiss Federal Institute of Technology, the optical spectrometer (a ground-based instrument), was used to collect shadow images of snow particles.

Data collection from the Electra aircraft’s PMS probes and S-Pol are the focal points of this research project. Comparing these data sets helped calculate important values including the density ($\rho$) of snow.

Previous Studies

Understanding the approach of analyzing snowfall rates by Magono and Lee (Magono and Lee, 1966) was a necessary step to this research.

Snowfall Classification

In 1966 Magono and Lee, scientists of Hokkaido University in Japan addressed the modification and enhancement of an older version of natural snow crystal classification created by Nakaya (Nakaya, 1954). With Nakaya’s permission, Magono and Lee modified his method by adding meteorological differences to snow crystal types.

Nakaya’s work was instrumental in providing science with a perfect classification of natural snow crystals from a physical point of view. The updated classification, by Magono and Lee had never been done before. Their motivation was to bridge the gap between physical and meteorological natural snow crystal classifications.

Nakaya’s work resulted in the temperature versus super saturation diagram (T-s diagram). The T-s diagram provided 38 classifications of snow crystal formation, but was insufficient from a meteorological standpoint. This classification method
lacked detailed classification of unsymmetrical or modified crystal types. For example, Nakaya’s research classified two types of needlelike snow crystals. The first type of needlelike classification was clearly defined, but the remaining type was not clearly defined. Through Magono and Lee’s meteorological investigation clear classification of the second type of needlelike crystal was possible. This second type of needlelike crystal is classified as a sheath.

Magono and Lee spent approximately 10 years determining meteorological differences for snow crystals. The conditions present in Nakaya’s T-s diagram are similar to the conditions in Magono and Lee’s modifications of the T-s diagram.

In order to modify Nakaya’s classification method Magono and Lee first extended snow crystal classifications from 38 to 80. Magono and Lee secondly sketched the natural snow crystals. Thirdly, a linear diagram was created displaying crystal classifications with the transition in temperature. And finally, Magono and Lee created a diagram, which showed the temperature and super saturation conditions for the growth of each type of natural snow crystal.

In viewing this diagram you can determine the meteorological conditions within which each natural snow crystal can exist by viewing the temperature and water saturation rate for each of the snow crystal classifications. For example, at temperatures between −10 and −20 °C and air that is super saturated with moisture, you get the formation of very complex dendritic crystals (common star shape). The same goes for temperatures between −6 and −8 °C where you get the formation of sheath type snow crystals, which are in the needle type snow crystal scheme. The original needle type snow crystal forms in the temperature range between −4 and −6 °C. These same needle type crystals also form between −25 and −29 °C (at the humidity of air), which is below the temperature at which the air becomes saturated with moisture.

There are uncertainties involved with the Magono and Lee scheme. The uncertainties result from the inaccuracy in determination of the cloud or “mother cloud” from which the snow crystal originated and also the clouds exact humidity. It is difficult to obtain the exact humidity of the mother cloud in cold temperature because it is not easy to determine the cloud from where the snow crystals originated. Despite several uncertainties, the Magono and Lee scheme is the most widely used and accepted classification of natural snow crystals.

As you can understand, natural snow crystal formation is a very complicated process that goes beyond Nakaya’s T-s diagram. For this research project it is important to know the ways in which snow crystals are formed and classified because it sheds light on the ways that crystals fall to the earth. For example, different types of snow crystals (i.e. needle, dendritic, bullet shaped, etc.) have
different densities. Therefore their fall velocities are different. Some snow
crystals fall to the earth much faster than others.

In order to estimate snowfall rates it is imperative to know how much water is
brought to the earth in each crystal through its density ($\rho$). A determination of
how much water is brought to the earth is found in the habit (type) of the snow
crystal. Each habit is different. Some crystal types may be more compact and
have higher density or very fragile with air inclusions and have low density.

**Calculating Raindrop-Size Distribution**

Extensive studies of raindrop size distributions have been occurring for over 40
years. Many techniques for raindrop sampling have been developed but none as
popular and widely used in meteorology as the Marshall and Palmer (Marshall
and Palmer, 1948) distribution.

The Marshall and Palmer distribution can be used to calculate rain rate (i.e.,
mm/h), liquid water content (i.e., $g/m^3$) and radar reflectivity ($mm^6/m^3$). The
Marshall and Palmer relationship is convenient because it gives an approximation
of size distribution for raindrops as a function of rain rate. This is given by the
following formula:

$$N_D = N_0 e^{-\Lambda D}$$

where $N_D$ is the number of raindrops per cubic meter per category, $D$ is the
diameter, $N_0$ is the intercept parameter, and $\Lambda$ is the slope.

Using this relationship with a specific rain rate, further calculation of the number
of raindrops per unit volume and raindrop size interval for a particular storm can
be made. Once these are calculated then they can be used to determine the
liquid water content.

Marshall and Palmer found that there is a relationship between radar reflectivity
($z$) and rain rate ($R$). Better known as the $z$-$R$ relationship. This relationship
translates to the power law:

$$z = aR^b$$

Where $z$ is the radar reflectivity factor and $R$ is the rain rate.

In the power law $a$ and $b$ are constants that are dependant on the particles
habit. By measuring drop-size distributions one can calculate the $z$-$R$ relationship.
In order to calculate $a$ and $b$ in the $z$-$R$ relationship, Marshall and Palmer plotted
rain rate on the $x$-axis against the reflectivity on the $y$-axis to determine the
relationship between both parameters.

Marshall and Palmer calculated the most commonly used $z$-$R$ relationship to be:
\[ z = 296R^{1.47} \]

This has been the basis for most of the research that calculates rainfall amounts from radar data.

The radar can provide pertinent quantitative information on rainfall with good temporal and spatial resolution. But the question remains, what about calculating rates for snowfall? There are many uncertainties about these computations. The rate of snow is usually converted to liquid and measured in mm/h, similar to rainfall of melted water.

**The Instruments**

The MAP field project collected ground-based, airborne, and radar measurements. Each of the instruments measured snowfall. They played a specific role in collecting data.

The ground-based measurements were done by an optical spectrometer. It records shadow images of the snow particles at a distinctive spot on the ground.

The Electra aircraft had PMS probes, which were mounted onto each wing. The aircraft flew through all portions of the storm (recording shadow images as well as collecting information about the precipitations type, shape, and size).

Lastly, S-Pol was used to capture the third precipitation dataset. Each of the instruments has its setbacks.

**How collected data works**

By collecting data with the optical spectrometer we get information about the precipitation particles that is thought to be true. It measures flux \( f \), which is how many particles per time (number of particle per \( m^3 \)) fall to the earth, and particle velocity \( v \).

The aircraft on the other hand measures concentration (number of particle per \( m^3 \)), and \( f \) as well as rain rate can be calculated by referring to the relationship between snow particles diameter-velocity and diameter-mass.

This shows the relationship:

\[
\begin{align*}
D &\rightarrow v \\
D &\rightarrow m
\end{align*}
\]

However, the ground optical spectrometer measures particle velocity and the aircraft does not. Knowing the velocity helps determine the rate at which precipitation particles fall to the earth.
Diameter of Precipitation Particles

In reviewing the article by Marshall and Palmer it is known that velocity for raindrops can be given as a function of diameter and diameter of raindrops is constant for each size. The diameter of snow changes with habit (type) and material phase (water/ice/ice type). This project focuses on calculating several components of snowfall by using the aircraft and radar. If diameter and information about the crystal types is known then calculating the density for snow is possible. If the precipitation particles density can be determined then future research can be done to determine the precipitation particles terminal velocity, by comparing what the aircraft saw in relation to what the radar scanned and preparing a histogram as follows:

\[
\begin{align*}
\text{(terminal velocity)} \quad v_t^1 \\
\text{D (diameter as seen from the aircraft)}
\end{align*}
\]

The radar is an important instrument. It is perfect for measuring snow. It provides information on the entire storm at the speed of light and measures at different elevations. The radar provides information on the storm above, within, and below the cloud layers, and is less expensive than constantly flying the aircraft into storms. On the opposite end, the aircraft provides information about the precipitation particles within the storm that is not seen by the radar, but is very expensive and will only fly at specific altitudes dependant on air traffic control.

The radar is the best instrument for measuring snowfall rates but has never been used to estimate snowfall before.

How “S-Pol” Works

Using S-Pol’s radio detection and ranging capabilities was a challenge because it was never used to estimate snowfall rates. S-Pol is a complex instrument that deserves an introduction on how it works.

S-Pol emits a pulse of energy in the form of a 10 cm wavelength. The amount of energy emitted from the radar releases into the atmosphere and reflect back according to the target that it hits. The target (precipitation) returns a wave that is dependant on particle size. Bigger particles return greater energy to S-Pol. The returned energy is related to the radar reflectivity factor (Z), which is much less energy than the radar originally emitted\(^i\).

\(^i\) \text{ } v_t \text{ as measured from observed evidence/analytical formula from laboratory data.}
The dimension of the particles was important for calculating \( z \), the summation over a unit volume of the particles diameter to the power of 6:

\[
z = \sum v N_i D_i^6
\]

This will be explained in the section titled technicians vs. scientist's interest.

The radar gives the summation of the particles weighing the larger particles it sees with higher precedence. S-Pol's 10 cm wavelength is a good size for measuring snowfall precipitation. The 10 cm radar wavelength is large enough to be in the Rayleigh scattering regime for the largest to the smallest precipitation particle. Precipitation particles in storms have a maximum size of:

- 5-6 mm in diameter for raindrops,
- 3 cm in diameter for snowflakes, and
- 0.1 mm in diameter for cloud droplets.

When S-Pol receives a (received) power from the precipitation, this power is related to the summation of the particles, over a unit volume with the diameter to the power of 6:

\[
z = \sum v N_i D_i^6
\]

Marshall and Palmer found that there is a relationship between \( z \) and \( R \). The most commonly used \( z-R \) relationship is for stratiform rain:

\[
z = 296R^{1.47}
\]

where \( z \) is in mm\(^6\)/m\(^3\) and \( R \) is in mm/h.

A calculation by Gunn and Marshall (Gunn and Marshall, 1958) found that the \( z-R \) relationship for aggregate snow is:

\[
z = 2000R^{2.0}
\]

**What are \( z \) and \( z_{\text{eff}} \)?**

There are two types of values that this research first looked at. They are \( z \) and \( z_{\text{eff}} \). When referring to both keep in mind that they are not used interchangeably. \( z \) and \( z_{\text{eff}} \) refer to the radar reflectivity factor, where \( z \) is related to the amount of energy that is returned to the radar by spherical shaped raindrops. The \( z_{\text{eff}} \) in \( z_{\text{eff}} \) has been added to take into account measurements of all other precipitation particles that were non-spherical shaped (i.e. snow flakes and snow crystals).

The diameter (D) of precipitation particles is important. Using D and material phase (water/ice/ice type) it is possible to calculate how much water falls to the earth. Calculating the volume of spheres is simpler than of non-spherical objects. Calculation of non-spherical particle shapes is more complicated because D
fluctuates. For example, how is D of a compact plate ice crystal measured (non-spherical)?

(Bently, 1962)

How is D of a capped column ice crystal measured (non-spherical)?

(Bently, 1962)

Calculation of z from the aircraft data and comparing to z_{eff} allow to determine the density for snow particles. I will refer to this later in the paper.

Technicians vs. scientist's interest

There are several calculations that must take place before z can be determined. The aircraft data provided measurements of particle size (D), number per size per category, and material phase (water/ice/ice type). From this information, calculating z was possible.

The aircraft probes provided snowfall shadow images that looked like this:
The PMS probes sorted the snowfall by concentration per size as a function of diameter:

**size distribution graph**

From the aircraft $z$ was computed using the equation that follows:

$$z = \sum N(i) D_i^6$$

where the radar reflectivity factor ($z$) is equal to the summation of all particles per m$^3$ with a distinctive diameter times the diameter ($D$) of the particles ($i$) to the power of 6.

The received power, which is recorded by the radar, depends on radar constants (i.e. gauge, antenna gain, wavelength, beam) dependant on the radar type (i.e. wavelength). The radar formula is:

$$P_r = \pi^2 P_t g^2 \theta \phi h |K|^2 \sum D_i^6 / (1024 \ln(2) \lambda^2 r^2)$$

This equation allows calculating reflectivity from the received power ($P_r$). Generally this formula can be written as:

$$P_r = C z$$

where $C$ is an instrument specific constant.

**Received Power ($P_r$) and Radar Reflectivity ($z$)**

Radars record $P_r$. From $P_r$ and $z$ can be deduced but $|K|^2$ has to be assumed. As the aircraft penetrates a storm $|K|^2$ can be assumed using the estimated particle density according to:

$$|K|^2 = \rho^2 0.2$$

**The Radar and $|K|^2$**

The backscattering energy of the radar is larger for precipitation particles comprised of water than for particles comprised of ice. This is due to the difference of the refractive index $|K|^2$. This index is approximately 4.5 times larger for water ($|K_{wi}|^2 = 0.93$) than for solid ice ($|K_{cel}|^2 = 0.197$). Additionally, frozen precipitation particles seldom have solid ice particles. Mostly they have air
inclusions and can therefore be considered as ice-air mixtures. For these particles the refractive index is lower than the index for solid ice. A good approximation for the refractive index of graupel is:

$$n_{\text{graupel}}^2 = \rho^2 0.197$$

where $\rho$ is the density of the graupel particles. This approximation is used in the present study and will be outlined in more detail below.

Even when the radar is measuring snowfall, the refractive index in the radar equation is set to the index of water. In case of solid ice particles the reflectivity will be displaced by 5-7 [dB(Z)] (decibels). In order to obtain $Z_{\text{eff}}$ from the received power, we have to solve the radar equation in the section titled technicians vs. scientist's interest.

**Linear and Logarithmic Values**

The radar reflectivity factor ($Z$) is a meteorological parameter determined by particle size and number in a sample volume. Linear volumes for determining weather range from the smallest (.001 mm$^6$/m$^3$) in the fog layer to the largest (30,000,000 mm$^6$/m$^3$) for hail. The large range of values that $Z$ can have is more convenient to deal with when transforming into logarithmic radar reflectivity values as in this equation:

$$Z = 10 \log_{10} \left( \frac{Z}{1 \text{ mm}^6/\text{m}^3} \right)$$

This shows the logarithmic radar reflectivity factor $Z$ compared to the non-logarithmic form $z$. In the logarithmic form, $Z$ is measured in decibels dB(Z). The linear form $z$ is measured in mm$^6$/m$^3$. Using dB(Z) values are common. For example: -30 dBZ for fog and +76.5 dBZ for hail compared to linear values of 0.001 mm$^6$/m$^3$ for fog and 30,000,000 mm$^6$/m$^3$ for hail.

**Content**

This project has matched radar and aircraft data sets, compared the reflectivity from both to deduce snowfall density, and used the calculated density to improve estimated snowfall rate through the Z-R relationship.

**Matching data sets**

For this research it was important to use aircraft data to determine exactly what was occurring within the storm at the exact elevation, date, time and azimuth as compared to the radar. Matching aircraft data with radar data was necessary because the aircraft measurements provided detailed and truthful information about the types of particles the radar scans saw.
The matching program developed by my scientific mentors and I measured overlapping data sets of snow from the same volume. There were numerous amounts of data collected from the aircraft and radar during the MAP field experiment. Manually analyzing both data sets was time consuming. The matching program provides an efficient way to get good areas where the aircraft flies at the exact location or in close proximity of the radar. This is important in understanding precipitation as seen by the aircraft and radar.

The matching program looks at the aircraft data first. It matches the aircraft position and time with the closest azimuth and elevation from the radar scans. The aircraft is measured by x, y, and z coordinates. The matching program finds the best x, y, and z coordinate radar data that correlate with the aircraft. The matching program has a time restriction where the radar has to be between -300 to +300 seconds (–5 to +5 minutes) from the aircraft in order to give the best data match. Then the program finds the best distance between the aircraft and radar beam. This procedure is repeated every second following the flight track of the aircraft.

A second restriction was set: the distance between the radar beam and the aircraft position has to be less than 500 meters in order to properly match. The matching program also does a correction of the wind flow. This is necessary, since the precipitation particles are carried away and will be at a different location from where the radar is scanning several minutes later. Finally the matching program provides the logarithmic radar reflectivity factor for the best match along the flight track of the aircraft.

Density

Water has a density of 1 kilogram per liter (kg/l). This does not change regardless of the size of the raindrops or of the type of cloud these raindrops fall from. However, density for snowfall is not easily calculated because snow has various shapes and sizes.

Crystals differ and knowing the particle size (diameter), concentration per size, and particle phase (water/ice/ice type) enables us to estimate their density. As mentioned earlier the aircraft provides this information. Radar reflectivity (Z) is calculated from this. The radar measures power returned (P_r) from which Z_{eff} is calculated. This is dependent on particle size (diameter), concentration per size, and particle phase (water/ice/ice type). The variables z and Z_{eff} were provided by the matching program at the same location and time.

Reflectivity to deduce density

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In the next step the reflectivity (z) calculated from the aircraft data are then compared to the reflectivity (Ze) recorded by the radar. The density of snow and ice particles can be estimated using the following formula:

$$0.93 \text{Ze} = 0.197 \rho^2 z$$

The left hand side represents the reflectivity recorded by the radar deduced from the radar equation in the technicians vs. scientist's interest section. This quantity is then multiplied by the refractive index of water. This is necessary since the power received by the radar was divided by |Kw|^2 in order to obtain Ze even in the case where precipitation particles were comprised of ice.

The right hand side represents the reflectivity calculated according to \( \sum_i N_i D_i^6 \) Multiplied by the refractive index of graupel particles as introduced in the section the radar and |K|^2 where density can be solved if the power received (Pr) from the radar and the information from the PMS probe (\( \sum_i N_i D_i^6 \)) is known.

Using density to calculate rain rate:

The matching program and the calculated density for the snow particles were used to calculate an estimated rain rate. This was done using the following formula:

$$R = \rho \pi/6 \sum_i N_i D_i^3 v_i (\rho, D_i)$$

where R represents the rain rate and v_i the terminal fall velocity of the ice particle. The estimated density is used—first, to estimate the amount of water in each ice particle and second, to estimate the velocity with which each ice particle (\( \rho \pi/6 D_i^3 \)) falls to the ground (v_i (\( \rho, D_i \))).

In a final step the estimated rain rate is correlated with the reflectivity recorded by the radar (Ze). Different Z-R relationships can be deduced for different ranges of density.

Results

This project closely analyzed one Intensive Observing Period (IOP). A good match between aircraft and radar data was found in this case.

During the MAP field experiment Eszther Barthazy (ETH Zurich) reported that the September 20, 1999 IOP was successful in collecting microphysical data. Three hours of good data were available. Precipitation was widespread and stratiform and this is also reflected in the microphysical data. Ice crystals, snowflakes, and graupel particles were observed at the flight level with nearly constant temperature (-16 degrees C).

The matching program was used to provide reflectivity for the aircraft and radar. The entire flight track was graphed using aircraft and radar reflectivity. It
showed that the mean density of the entire flight track was 0.078 kg/l. The density for water is 1 kg/l. From figure 10 we can notice a relationship between the reflectivity calculated from the aircraft (Z) and the reflectivity deduced from the radar (Zeff). The particles had a lower density than water.

Figure 10 focused on averaging 10 seconds periods for the entire flight track of September 20, 1999. The points on figure 10 are separated into three groups. The estimated densities for particles differ for each group. In general they are less than the density for water particles. The differing densities are reflected in the PMS probe images provided by the aircraft. The images provided accurately depict what the PMS probes saw as it flew through the storm. The PMS probe images where the particle shadows look nearly spherical represent their higher density particles. As soon as the particles appear with more branches then the density decreases.

In figure 11 the relationship between the difference in reflectivity and the density (ρ kg/l) can be seen. Each difference given in dB(Z) provides a distinctive density, which is reflected in this formula:

$$Zeфф - Z = [dB(Z)] \rightarrow (ρ)$$

\[ Z-R \text{ relationship} \]

The Z-R relationship has had a long history in radar meteorology. This relationship measures rainfall but has serious problems in beam fillings, down drafts, difficulty in measuring corresponding samples, etc. This project has found an estimated Z-R relationship that will build upon previous Z-R relationships.

Figure 12 represents the Z-R relationship found in the September 20, 1999 IOP. Each point represents a 10 second average per unit volume. Compared with the Marshall and Palmer Z-R relationship for raindrops (dotted black line) in figure 12 shows a Z-R relationship for three different categories of snowfall. The densities of each category are:

- between 0 and 0.03 kg/l (low density depicted in blue),
- between 0.03 and 0.08 kg/l (medium density depicted in red), and
- between 0.08 and kg/l (high density depicted in green).

If the density of the precipitation particles is known the corresponding Z-R relationship allows to obtain an estimated rain rate from the reflectivity measurements of the radar.

**Conclusion**

There are some uncertainties associated with the results provided. These are:
1. The calculation of rain rate in terms of reflectivity is uncertain. The estimated rain rate provided by this research may vary by factor of 2 for a distinctive reflectivity. There is no proof from the ground that this rain rate is accurate. A direct comparison of the provided rain rate by a ground-based instrument (i.e. rain gauge) is needed to confirm the deduced Z-R relationship in this study.

2. The formula used to calculate the fall speed of the precipitation particles provides good results for graupel particles, but may not apply well with these particles. This is why the ground-based information is essential to validate the results provided.

3. The difference in the sample volumes of the aircraft compared to the radar.

Next steps

This research is a beginning step, which has not used the radar’s polarimetric capabilities. The immediate next step is to use “S-Pol’s” polarimetric capabilities to test if it would give a better density than provided in figure 10. This would mean that the project is closer to achieving its goal. The goal of this research is to use the radar’s polarimetric capabilities to predict rain rate for snow and cease use of the aircraft.

The timing is right for this research. First, because the MAP field experiment collected a great data set of aircraft and radar with good position and matches that is the best data set thus far. Secondly, the radar is of the newest generation and measures multiple parameters.

By using the multiple radar parameters, rain rate for snow will help when predicting floods, warning of water resource problems, and planning for agriculture..........

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1 See figure 1.
2 See figure 2.
3 See figure 3.
4 There were many other instruments used in MAP, but I listed are those relevant to this research.
5 See figure 4,5,6.
6 See figure 7.
7 See figure 8,9.
References:


"Electra"

PMS probe
"S-Pol"

10 cm wavelength
New optical spectrometer

with two vertical offset light beams
→ exact fall velocities

![Diagram of an optical spectrometer with labeled parts: Beam shield, Active measuring area, Light source, Two rows of Photodiodes, 10 mm distance.](image-url)
TRANSLATION IN TEMPERATURE

-40 (°C)
-35
-30
-26
-20
-15
-10
-5
0

figure 5
Fig. 2. Temperature and humidity conditions for the growth of natural snow crystals of various types.
How "S-Pol" measures power returned \( (P_r) \)

\[ \sum_i N_i D_i^6 \propto P_r \]

\( P_r \) depends on:
- Particle size (diameter) \( D_i^6 \)
- Concentration per size \( N_i \)
- Particle phase (water/ice/ice type)
Diversity of ice crystals:

- Needle
- Dendrite
- Sector plate

Banded column

Crystals
The Rimming Process:

Rimed Plates

Graupel

Hail
Theoretical relationship between reflectivity difference and density

reflectivity difference (Ze - Z) [dBZ]

density [kg/l]

mean density: 0.120452 kg/l

mean density: 0.0393208 kg/l
20 Sept. 1999

reflectivity 2DP [dBZ] vs. reflectivity radar [dBZ]

- Mean density: 0.00361198 kg/l
  Lin. corr = 0.616332

- Mean density: 0.0393208 kg/l
  Lin. corr = 0.897178

- Mean density: 0.120452 kg/l
  Lin. corr = 0.712753