FM-CW DOPPLER/POLARIMETRIC RADAR MEASUREMENTS OF THE MELTING LAYER IN RAIN CLOUDS

L.P. Ligthart, H.W.J. Russchenberg, W. Klaassen
Delft University of Technology
Department of Electrical Engineering
The Netherlands

1. Introduction

Doppler/polarimetric measurements were started in 1987 at the Delft University with focussing on S-band radar remote sensing of the melting layer in rain. The measurement campaigns are part of the Delft research program on radar propagation studies. The central theme in the studies is the determination of the particle size distribution of hydrometeors (rain, snow, melting particles, etc.) as a function of place and time. When the types of hydrometeors and their distributions can be measured by radar, the results can be used as inputs to calculate the co- and cross-polar characteristics of the forward scattering coefficients along a satellite path. The frequencies selected for the calculations are 12, 20 and 30 GHz, i.e. the frequencies of the ESA-Olympus satellite, which will be launched in 1989.

In order to derive the strongly varying distributions maximum use is made of capabilities of the Delft FM-CW radar i.e.

- the high range resolution of 30 meters
- the resolution in Doppler-velocity of 0.14 m/s
- the capability to determine simultaneously the Doppler and polarization characteristics of volume back scattering.

The resolution in range and Doppler velocity spectrum allows the verification of a melting layer model in which the dielectric properties, aggregation and break-up of melting particles can be taken into consideration. A summary of the melting layer is given in Section 2. Polarization measurements along the radar path are discussed in Section 3.

2. Melting layer

In moderate climates as in the Netherlands stratiform rain conditions are often satisfied. The stratiform rain originates from precipitation particles at high altitudes with geometries of small ice needles and plates. These particles may collide and form snowflakes. When falling snowflakes come at altitudes with air temperatures above the freezing point the melting occurs. In the final stage of melting the particles follow their paths downwards as raindrops. It is memorized that during non-stratiform rain strong convective motions in the air are responsible for generating different types of graupel and hail particles.

2.1. Melting layer model

For the melting layer model it is assumed that melting snowflakes have to be considered with height dependence only. The melting processes within the layer are generally dependent of the vertical air temperature gradient, the vertical air velocity, the initial particle size distribution before melting starts, the effects of condensation of water vapour on the melting particles and the effects of aggregation and/or break-up.

The above mentioned phenomena have their influences on the dielectric properties of a single melting particle and therefore on the backscattering properties as measured with radar. The dielectric constant ε_{av} of the melting particle is dependent of

- the initial density of the snowflake just before melting starts

- the ice-water-air mixture within the melting snowflake.
The calculation of the dielectric constant makes use twice from the Maxwell-Garnet theory

1st : for the dielectric constant of the ice-water mixture assuming elliptical ice inclusions in a water matrix

2nd : for the dielectric constant of the wet ice-air mixture.

The reflectivity excess Z_x [dB] of a melting particle is defined relative to the reflectivity of the resulting raindrop after melting and becomes [1]

$$Z_x = 20 \log\{(\varepsilon_{av} - 1)(\varepsilon_w + 2)\} - 20 \log\{(\varepsilon_{av} + 2)(\varepsilon_w - 1)\}$$

where ε_w is the dielectric constant of water.
Calculations of Z_x indicate strong differences with the -frequently used- model for melting snow in which a melting snowflake consists of two concentric spheres. The outer sphere is then considered as a water shell around a spherical snowflake.

2.2. Melting layer characteristics
In order to verify the melting layer model the following melting layer characteristics are measured with vertically pointing antennas:

1. The reflectivity Z_r in the rain just after melting
2. The maximum reflectivity excess Z_{xm} during melting
3. The bright-band thickness B
4. The mean Doppler velocity V_{dr} just after melting
5. The mean Doppler velocity V_{do} just before melting

The determination of B makes use of assumptions for defining the upper and lower boundary. In stratiform rain it appears that the upper boundary can be accurately estimated at the height where the reflectivity in the bright band is dropped to the value of Z_r. The lower boundary coincides with the height where the Doppler velocity reaches its maximum value minus 0.5 ms^{-1}. Z_r and V_{dr} are the measured values 100 m below this lower boundary.
Characteristics 1 to 4 are used to determine the input parameters of the model by a fitting routine. V_{do} is used for verification.

2.3. Model verifications
Observations of distinct bright bands -measured on different days- have been classified based on the reflectivity Z_r and velocity V_{dr}. Simulations -with and without aggregation and/or break up- show good agreement with the measurements.
The Doppler spectra are calculated per range bin and at minimum time intervals of 0.3 s. Since mean Doppler calculations are reliable at these small time scales, the spectra can be used also to study the vertical air velocity characteristics. The value of the melting layer model can be demonstrated also during non-stratiform rain showers. Even when detection difficulties exist to characterize the melting process at some instant, the time dependence gives sufficient insight into the width B, the maximum reflectivity excess Z_{xm} and the relative height at which Z_{xm} is measured.

3. Radar polarimetric measurements

The Delft FM-CW radar is a Doppler/polarimetric type of radar system since two polarizers can change the linear polarization at the seperated receiving and transmitting antennas. Full polarimetric data per range cell can be extracted assuming correlation between successive measurements. The correlation time can be enlarged by using the resolution in the Doppler velocity domain. Correlation measurements within Doppler resolution cells of 0.14 ms^{-1} gave support to do correlated polarimetric analysis of hydrometeors over time intervals of several hundreds of milli-seconds.

In case of non-vertically pointing antennas the multi-polarization measurements with the Delft radar allow to do detailed Doppler/polarimetric studies on hydrometeors.
During these measurements the elevation angle of the antennas was fixed at 30 degrees, while the azimuth angle was adjusted so that the radar path was perpendicular to the mean wind direction.
In the analysis a gamma rain dropsize distribution is assumed. For this distribution yields

$$N(D) = N_0 D^m \exp\{-(3.67 + m)\, D/D_0\}$$

where

D: equi-volume diameter of raindrops

m: order of the distribution

From the polarimetric measurements the differential reflectivity Z_{dr} and the linear depolarization ratio L_{dr} are calculated. Z_{dr} and L_{dr} are defined as

$$Z_{dr} = Z_{HH} - Z_{VV} \quad [dB]$$
$$L_{dr} = Z_{HV} - Z_{HH} \quad [dB] \qquad \text{H/V: horizontal/vertical polarization}$$

Preliminary investigations in stratiform rain with a distinct melting layer have been done. A first example is given in the figure in which Doppler and Polarimetric results are shown. Calculated rain intensities -derived from the gamma (m = 0 and m = 2) and from the Marshall-Palmer distributions- have been compared with measured rain intensities at a distance of 650 m from the radar.

Conclusion

In order to participate in 12, 20 and 30 GHz satellite propagation experiments Delft University of Technology owns a Doppler/polarimetric radar. A part of this research deals with the possible hindrance of the melting layer in these satellite links. In this paper a melting layer model is introduced which is verified based on Doppler radar measurements. Attention is paid to a qualitative description of the phenomena in and under the melting layer in relation with the changes in the electro-magnetic backscattering properties as measured by the radar. High resolution measurements in range and in Doppler velocity spectra during stratiform rain justifies the melting layer model characteristics.
It can be shown that within 0.3 seconds a reliable Doppler reflectivity profile along the radar path can be measured. A start is made with Doppler/polarimetric measurements on hydrometeors. Differential reflectivity and linear depolarization ratio measurements are possible. The radar potentials for determining the gamma dropsize distribution are illustrated.

1. W. Klaasen, "Radar Observations and Simulation of the Melting layer of Precipitation", Journal of Atmospheric Sciences, december 1988.

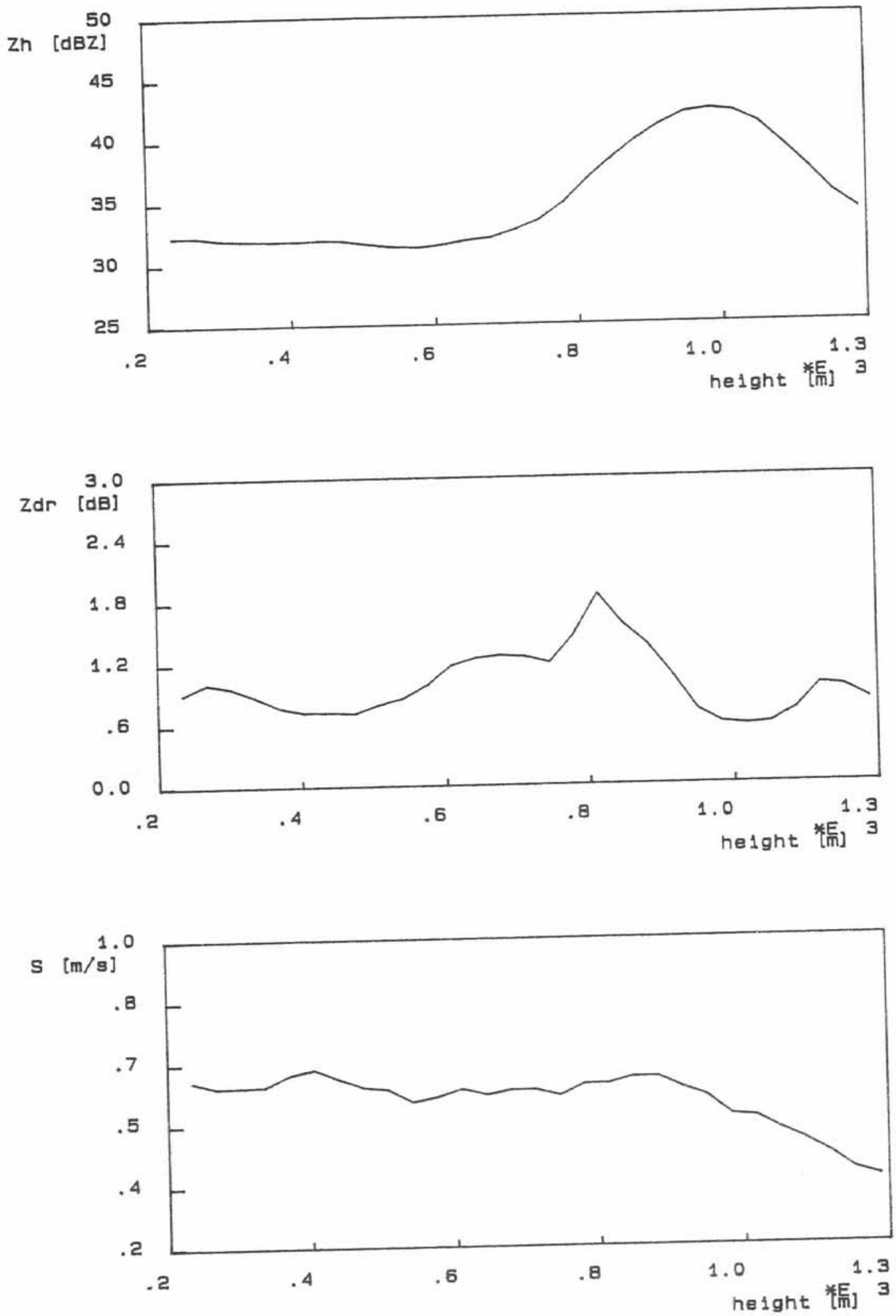

Figure Z_{HH}, Z_{dr} and spectrum width S as function of height.