Polarimetric Weather Radar Remote Sensing

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State of the Art of Weather Radar

- Doppler and dual-polarization
- Cancellation of ground clutter
- Correction of attenuation and propagation effects
- Automatic quality control
- Identification of hydrometeors
- Quantitative estimation of precipitation
Weather Radar

Combination of 16 weather radars of Deutscher Wetterdienst.

Weather radars are well suited to locate precipitation.

Meteorologists require more:

- how much rainfall?
- what kind of hydrometeors?
- how will the weather be in 10 .. 90 minutes?
Radar Principle

Radar: Radio Detection and Ranging

A weather radar measures the power (and phase) of a transmitted electro-magnetic wave packet reflected by a particle:

Radar equation for volume targets:

\[ P_r = \frac{P_t g^2 \lambda^2 \theta_0^2 h}{1024 \ln(2) \pi^2 r^2} \sum_{i} \sigma_i \]

Particles smaller than the wave length:
(C-Band \( \lambda = 5 \text{ cm} \), \( D < 5 \text{ mm} \)) Rayleigh-scatter

Reflectivity factor
Unit: mm\(^6\) m\(^{-3}\)
logarithmic unit: dBZ

\[ \sigma_i = \frac{\pi^5}{\lambda^4} |K|^2 D_i^6 \]
Radar Reflectivity Factor

- Hail
- Severe rain, hail
- Strong rain, graupel
- Rain
- Light rain
- Drizzle
- Clear-air

Map showing radar reflectivity factor with color scale.

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Martin Hagen, WFMN09, Chemnitz, 25 - 27 Nov. 2009
Cloud and precipitation particles have different shapes, phase, size and falling behaviour.

- scattering properties
- Polarization

Precipitation is directly related to atmospheric motion.

- Hydrometeors are displaced
- Doppler shift of waves
Polarization and Doppler Radar Development

1960
Doppler Radar (research)

1985
Doppler Radar (operational in Europe)

1995
bistatatic Doppler Radar

2002
dual-Doppler+Lidar Assimilation in NWP

1976
polarimetric Radar (research) (R-Z-ZDR)

1986
polarimetric Radar (operational) (R-KDP)

1990
polarimetric Radar (operational, without substantial success)

2004
polarimetric Radar (operational, MeteoFrance)
Weather Radars in Europe (2005)

(almost) all are Dopplerized

rapidly increasing number of polarimetric radars
Polarization Doppler Radar POLDIRAD

1986 installed as the first fully polarimetric weather radar in Europe. Operations normally for research, not for operational service

www.pa.op.dlr.de/poldirad

Samples of research projects:
- Support of hail fighting in the area Rosenheim / Miesbach / Bad Tölz
- Thunderstorm and hail
- Propagation of waves
- Aircraft icing
- Vertical transport of pollutants by thunderstorms
- Thunderstorm and lightning
- Wake turbulence
- Aviation, thunderstorms and snow

Technical Characteristics

- Frequency: 5.5035 GHz
- Wave Length: 5.45 cm
- Peak Power: 250 kW
- Pulse Rep. Freq.: 400 - 2400 Hz
- Pulse Length: 0.5, 1.0, 2.0 µs
- Beam Width: 1.0°
- Maximum Range: 300 km
- Products: Reflectivity, Doppler Velocity, Diff. Reflectivity, Depolar. Ratio, Different. Phase
The Doppler effect describes the observed frequency change at a relative motion between:
- signal source and observer (propagation speed of the signal c, relative motion with speed v)

\[
f = f_0 \left(1 \pm \frac{v}{c}\right)
\]

example sound: \( v = \pm 20 \text{ m/s}, f_0 = 5 \text{ kHz}, c = 300 \text{ m/s} \Rightarrow f = 5 \pm 0.333 \text{ kHz} \)

example radar: \( v = \pm 20 \text{ m/s}, f_0 = 5 \text{ GHz}, c = 3 \times 10^8 \text{ m/s} \Rightarrow f = 5 \pm 0.000000333 \text{ GHz} \)
Interpretation of the Doppler Velocity

blue/green towards radar
red/orange away from radar
Uniform Wind Technique

Assumption of a constant wind field along a segment of a circle. Average over a sector segment (app. 20 km x 20°)

\[ v_r = u_0 \sin \phi \cos \theta + v_0 \cos \phi \cos \theta \]

\[ v_t = \frac{\partial v_r}{\partial \phi} \]

Size of segment:
- get \( \frac{\partial v_r}{\partial \phi} \) sufficient accurate
- wind constant within segment.
Dual-Doppler Radar Observations

- For research and small-scale nowcasting high resolution 3-D wind fields are required.

- Combination of Doppler observations from different directions using more than one radar.
Dual-Doppler Analyse

Doppler-velocity measured by the individual radars

Combination to the horizontal wind field

(flow relative to storm motion)
Doppler Wind Field using dual-Doppler and Uniform Wind

DWD Wind 3 km

2 June 2001 1156 UTC

Reflectivity in dBZ

-10 5.0 10 15 20 25 30 35 40 45 50

20 m/s

100 km

Radar: MHP TUR

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Bistatic Doppler Radar

1 active Doppler radar
+ one or more passive bistatic receivers.

DLR system:
first system operating with a magnetron
Bistatic Doppler Radar

9 July 2002
1557 UTC
Elevation 5.4°
Polarimetric Radar Observations

Polarizations:
- linear
- circular
- elliptic

Modes:
- simultaneous H and V transmit and receive
- alternating H and V transmit (pulse to pulse), simultaneous H and V receive

Rain
Graupel
Hail
Polarimetric Radar Observations

Polarizations:
- linear
- circular
- elliptic

Rain
Graupel
Hail

Polarimetric Radar Products:
- Reflectivity $Z$
- Differential Reflectivity $ZDR$
- Depolarization Ratio $LDR$

Correlation coefficient between H and V: $\rho_{HV}$
Differential propagation phase between H and V: $\phi_{DP}$
Example: shape of falling raindrops

Falling raindrops (app. 2 – 8 m/s) have an oblate shape due to aerodynamics.

Observations in a vertical pointing wind channel (Univ. Mainz), 5 mm drop.

\[ D_{eq} = 2.6 \, \text{mm} \quad 3.4 \, \text{mm} \quad 5.8 \, \text{mm} \]

\[ D_{eq} = 7.4 \, \text{mm} \quad 8.0 \, \text{mm} \]
Rain rate and radar reflectivity

Empirical relation between rain rate $R$ and reflectivity $z$

$$R = a z^b$$

$z$ in mm$^{-6}$ m$^{-3}$

$R$ in mm/h

Coefficients $a$ and $b$ depend on drop size distribution.

7000 1-minute drop size distribution, Oberpfaffenhofen, 1996
Rain rate and polarimetric radar measurements

Additional information about raindrop size distribution by differential reflectivity: sensitive to large drops.

\[ R = a z^b ZDR^c \]

Small errors in polarimetric quantities can give large errors in rain rate estimation.

7000 1-minute drop size distribution, Oberpfaffenhofen, 1996
Classification of hydrometeors

Höller et al., JAS 1994
Thunderstorm line observation 12 Aug. 2004
Hydrometeor classification 12 Aug. 2004

The image shows a color-coded map illustrating various types of hydrometeors. The legend indicates different categories such as small raindrops, large raindrops, dry hail, wet hail, and a variety of hail and rain combinations. The map is color-coded, with different colors representing different ranges of reflectivity dBZ values.
Classification by Vivekanandan et al. (1999)

- Additional parameters like correlation coefficient $\rho_{HV}(0)$ and specific differential phase $K_{DP}$.
- Decision tree becomes difficult to define.
- "Fuzzi Logic" will be used to identify the most probable particle class.
Reflectivity

Differential reflectivity

Classification

Cloud Drops, Drizzle, Light Rain, Moderate Rain, Heavy Rain, Hail, Rain/Hail, Graupel/Small Hail, Graupel/Rain, Dry Snow, Wet Snow, Ice Crystals, Irregular Ice Crystals, Droplets, Super-Cooled Liquid Water, Insects
Attenuation and Propagation degrades Classification

- Attenuation can’t be recognized easily (C-Band)

- Frequently observed are negative ZDR values behind reflectivity cores

- negative ZDR is not expected in rain
Attenuation: Vertical Cross-Section (RHI)

- strong attenuation at 3 – 4 km height (below melting layer), high Z and LDR indicate presence of hail.
- hail spike (flare echo) ????
- must be wet melting hail with shedding water shell.
- unknown particle properties → no correction possible
Quality index field for polarimetric radar products

Quality control settings for use of polarimetric data for rain rate estimation.
From Research to Application

Further presentations:
- ground clutter
  (Jens Reimann)
- hydrometeor classification
  (Jörg Steinert)
- Doppler moments
  (Ondrej Suchý)
- rain rate estimation
  (Patrick Tracksdorf)
- attenuation correction
  (Tobias Otto)