Mesoscale Atmospheric Systems

Radar meteorology 2

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With material from H Wernli, I Zawadzki, and the radar colleagues at MeteoSwiss
A band of bands

<table>
<thead>
<tr>
<th>Frequency</th>
<th>λ</th>
<th>band</th>
<th>meteorological application</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-300 MHz</td>
<td>1-15 m</td>
<td>VHF</td>
<td>wind profiler, ocean surface motion</td>
</tr>
<tr>
<td>400-900 MHz</td>
<td>0.3-0.7 m</td>
<td>UHF</td>
<td>wind profiler</td>
</tr>
<tr>
<td>1 GHz</td>
<td>0.3 m</td>
<td>L-band</td>
<td>boundary layer wind profile</td>
</tr>
<tr>
<td>2-4 GHz</td>
<td>7-15 cm</td>
<td>S-band</td>
<td>long-range precipitation radars</td>
</tr>
<tr>
<td>4-8 GHz</td>
<td>4-7 cm</td>
<td>C-band</td>
<td>long-range precipitation radars</td>
</tr>
<tr>
<td>8-16 GHz</td>
<td>2-4 cm</td>
<td>X-band</td>
<td>precipitation radars, marine radars</td>
</tr>
<tr>
<td>16-20 GHz</td>
<td>1-2 cm</td>
<td>Ku-band</td>
<td>radars</td>
</tr>
<tr>
<td>35 GHz</td>
<td>8.5 mm</td>
<td>Ka-band</td>
<td>precipitation and cloud radars</td>
</tr>
<tr>
<td>90-100 GHz</td>
<td>3 mm</td>
<td>W-band</td>
<td>cloud radars, Mie minimum</td>
</tr>
</tbody>
</table>
Part 1: Radar networking
Optimal wavelength for radar in the Alps

Arguments for C-band compared to S-band
• Better weather-to-clutter ratio ($\lambda^{-4}$ in Rayleigh approximation)
• Narrower beam and lower side lobes (for given antenna size)
• Better chances to detect weak echoes in snow over the Alps
• Installation and operations affordable on mountain peaks
• Receiver can be mounted on antenna (better sensitivity, no dual rotary joint)

Arguments for S-band
• Attenuation negligible
• Larger Nyquist interval

Swiss radar network
5.5 cm (C-band)
4th Swiss radar generation (MeteoSwiss)

Fully automatic

C-band
Volume-scanning
Dual-polarisation Doppler radar

with receiver-over-elevation-design

Lema, 1626m renewed 2011
Dole, 1682m renewed 2011
Albis, 938m renewed 2012
Plaine Morte, 2937m 2014
Weissfluh, 2850m 2016
Europe has a dense network of operational weather radars.

Composite is used for

- large-scale monitoring of precipitation,
- numerical weather prediction,

and increasingly also for

- applications in aviation, hydrology, climatology,
- and research.

http://eumetnet.eu/activities/observations-programme/current-activities/opera

OPERA programme manager: E Saltikoff, FMI
US radar network «NEXRAD»

- totally 159 S-band Doppler radars
- recently upgraded to dual-polarization technology
- good coverage in flat regions
- limited coverage in mountainous regions
Other networks

- Radar networks in many other regions around the world: Canada, Japan, Australia, …

- S-Korea: Exceptionally dense network thanks to the superposition of networks from several independent operators. Challenge due to orography similar to Switzerland.

Part 2: Meteorological processing
PPI (Plan Position Indicator): Measurements from a 360° scan with constant elevation angle, projected on the ground.

RHI (Range Height Indicator): Measurements from a scan with constant azimuth

HTI (Height Time Indicator): Measurements over time period with antenna pointing in the vertical direction

CAPPI (Constant Altitude Plan Position Indicator): Horizontal cross section at a selected height level through a volume of PPI scans. The x and y axes of the plot correspond to easting and northing.

HARPI (Height Azimuth Range Position Indicator): Vertical cross section at constant range through a volume of PPI scans. The x and y axes of the plot correspond to azimuth and height.
First measurements of new Plaine Morte radar during installation, November 2014
Quantitative precipitation estimation (QPE)

Reflectivity estimate of precipitation @ ground
D^6, D^3, D^4

Radar reflectivity Z

\[ Z = \int_0^\infty N(D)D^6dD \]

\[ dBZ = 10 \log_{10} \frac{Z}{Z_0} \]

Volumetric liquid water content W

\[ W = \frac{\pi}{6} \int_0^\infty N(D)D^3dD \]

Rainfall rate R

\[ R = \frac{\pi}{6} \int_0^\infty N(D)D^3v_t(D)dD \approx \frac{\pi}{6} \int_0^\infty N(D)D^4dD \]

N(D) is the drop size distribution

v_t(D) is the terminal fall velocity of drops
How can we estimate R from Z if N(D) varies so much?
Fortunately, we know a lot about N(D) and we can obtain reasonable estimates of R from Z using approximations, so-called Z-R relations.

And there is dual-polarization, that helps a lot …
Shape of falling drops

Raindrops falling with their terminal velocity are oblate.

Drops can be described as rotational ellipsoids with the axis $a$ and $b$.

Observations in a vertical wind tunnel

$D_{eq} = 2.6 \text{ mm} \quad 3.4 \text{ mm} \quad 5.8 \text{ mm}$

(small drops are spherical, large ones are oblate)

(Pruppacher & Klett)

$D_{eq} = 7.4 \text{ mm} \quad 8.0 \text{ mm}$
Dual-polarization radar

Dual polarization radars transmit and receive horizontally and vertically polarized electromagnetic waves.

Most dual-pol radars transmit H and V simultaneously, and process H and V of the return signal in parallel in 2 separate receiver channels.

Some dual-pol radars first transmit H and receive H and V, then transmit V and again receive H and V, but …
Why dual-polarization radars?

- Distinguish between meteorological (hydrometeors) and non-meteorological targets (ground clutter, birds, insects, aircrafts).
- Classification of hydrometeors (large drops, small drops, ice crystals, snowflakes, melting snow, graupel, hail).
- Better data quality (redundant receive channels, hardware monitoring, …)
- Correct for attenuation of radar signal in heavy rain.
- Better estimation of rainfall rates, especially in presence of large drops.
# Dual-polarization measurables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Measurable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_H$, $Z_V$</td>
<td>Reflectivity</td>
<td>particle size + number (precipitation rate)</td>
</tr>
<tr>
<td>$Z_{DR}$</td>
<td>Differential reflectivity $Z_H / Z_V$</td>
<td>particle shape (target id, rainfall rate)</td>
</tr>
<tr>
<td>$K_{DP}$</td>
<td>Specific differential propagation phase</td>
<td>particle shape (intense rain, target id, attenuation correction)</td>
</tr>
<tr>
<td>$LDR$</td>
<td>Linear depolarisation ratio $Z_{VH} / Z_H$</td>
<td>shape + orientation (target id, melting snow)</td>
</tr>
<tr>
<td>$\rho_{HV}$</td>
<td>Correlation coefficient</td>
<td>variety of shapes (target id)</td>
</tr>
</tbody>
</table>
### Target identification from dual-polarization

From theory and observations.

<table>
<thead>
<tr>
<th>Target</th>
<th>$Z$ (dBZ)</th>
<th>$Z_{DR}$ (dB)</th>
<th>KDP ($^\circ$ /km)</th>
<th>$\rho_{HV}(0)$</th>
<th>LDR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>10 – 55</td>
<td>0 – 5</td>
<td>0 – 10</td>
<td>≈ 1.0</td>
<td>&lt; -30</td>
</tr>
<tr>
<td>Ice crystals</td>
<td>&lt; 15</td>
<td>0 – 2</td>
<td>0</td>
<td>≈ 0.99</td>
<td>&lt; -30</td>
</tr>
<tr>
<td>Snow aggregates</td>
<td>&lt; 25</td>
<td>0 – 2</td>
<td>0</td>
<td>≈ 0.99</td>
<td>&lt; -30</td>
</tr>
<tr>
<td>Graupel</td>
<td>up to 40</td>
<td>≈ 0</td>
<td>≈ 0</td>
<td>&gt; 0.95</td>
<td>&lt; -30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.95 melting</td>
<td>&lt; -25 melting</td>
</tr>
<tr>
<td>Hail</td>
<td>up to 70</td>
<td>≈ 0</td>
<td>≈ 0</td>
<td>0.9 – 0.95</td>
<td>&gt; -25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.9 melting</td>
<td>-25 – -15 melting</td>
</tr>
<tr>
<td>Insects</td>
<td>&lt; 5</td>
<td>5 – 10</td>
<td>?</td>
<td>0.9 – 1.0 ?</td>
<td>&lt; -30 ?</td>
</tr>
<tr>
<td>Birds</td>
<td>&lt; 5</td>
<td>3 – 6</td>
<td>?</td>
<td>0.9 – 1.0 ?</td>
<td>&lt; -30 ?</td>
</tr>
<tr>
<td>Ground clutter</td>
<td>any</td>
<td>noisy</td>
<td>noisy</td>
<td>1 stopped</td>
<td>&gt; -20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.6 rotating</td>
<td>antenna</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Target identification from dual-polarization

From theory and observations.

In reality things are more complex:
- melting hail and graupel can have high ZDR and high KDP
- ice dendrites can have high ZDR
- (...)
Dual-polarization hydrometeor retrieval

Hail cell in Rubigen (BE) as seen by dual-polarization radar on Albis in operational mode (!) at 90 km distance.

Hydrometeor classification (Albis)

Bacic, Figueras, Grazioli, Gabella, Germann and Berne (2016)
Radar – raingauge integration

For demonstration purposes we have selected an example where the radar has severely underestimated rainfall at ground. In most cases, errors are smaller.

Space-time co-kriging with external drift with data transformation and sophisticated quality control

MeteoSwiss

Sideris, Gabella, Erdin, Germann (QJRMS, 2013)
Part 3: Meteorological studies
Stratiform precipitation and bright band

- vertical wind < ~ 1 m/s
- horizontal scale ~ 100 km
- stable stratification
- external lifting (e.g. through fronts or orography)
- in polar regions and in midlatitudes
Stratiform precipitation

Figure from Zawadzki et al (McGill)
Bright band

**Within melting layer:**
Particles have size of snowflake, but dielectric constant of water. On top, some stick together and form large aggregates.

► Layer of enhanced reflectivity («bright-band»).

**Below melting layer:**
Increase in dielectric constant and decrease in number density due to larger fall speed roughly have same effect but with opposite sign. (In reality more complex: break-up and more.)

► Before and after melting reflectivity is similar.

*Figure from Zawadzki et al (McGill)*
Some convective activity

Figure from Zawadzki et al (McGill)
Dynamics and microphysics

- light snow
- heavy snow
- riming
- supercooled cloud
- supercooled drizzle
- secondary ice
- bi-modal Doppler

Figure from Zawadzki et al (McGill)
Convective storms

HARPI display by Puigdomenech
With a little help from the public

We get about 14'000 hail reports from app users every year, a unique data source for radar hail research.

Hail cell of 6 June 2015

**MESHS:** maximum hail stone size from radar

**Overlay:** hail size reports from app users

*P Noti et al (Uni Bern, Mobiliar Lab, MeteoSwiss)*
Hail cell in forecast model

COSMO uses radar for analysis

Trefalt et al (2017)
Hail cell climatology

Radar hail mapping
2002-now

Data base with totally
> 30’000 hail cells

- Automatic detection
- Climatology
- Automatic alert

PhD projects LNisi, S Trefalt
Uni Bern, Mobiliar Lab, MeteoSwiss
Tornado visiting PARADISO field experiment

Adaptive high-resolution scanning by X-band radar
(triggered by C-band thunderstorm tracking)

PARADISO field experiment
(MeteoSwiss, armasuisse, EPFL, IACETH)
Diurnal cycle

Data
JJA (June-August) of 6 years (2005-2010)

Mandapaka, Germann, Panziera, QJRMS, 2012
Flooding in Maggia river  18 events in 2005-2012

9 most intense floods

- Rank 9-18 floods

void