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Automatic diagnosis and quantification of bird migration with weather radars

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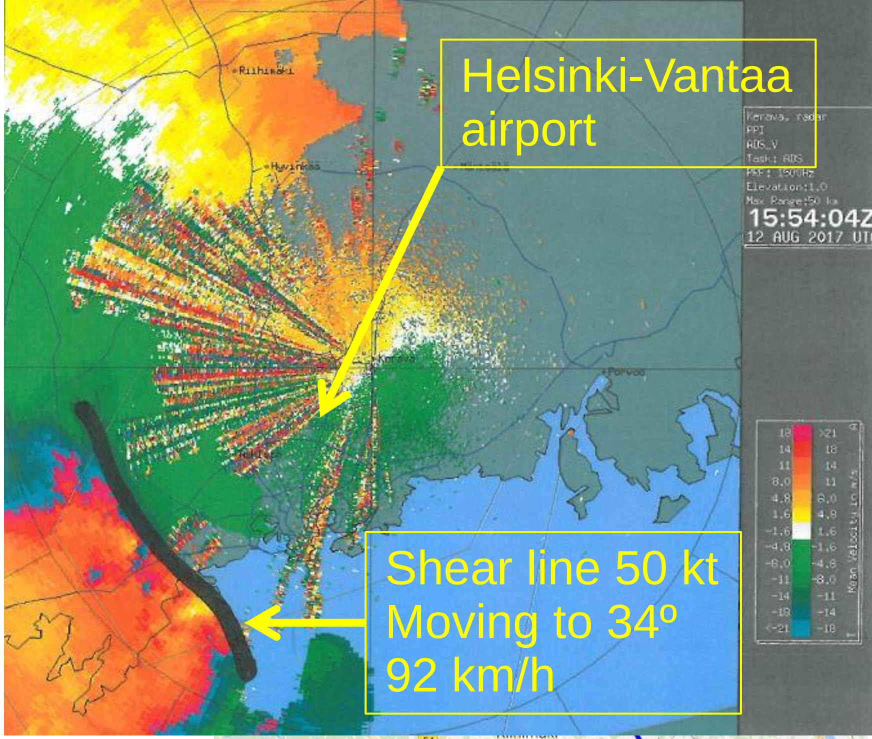
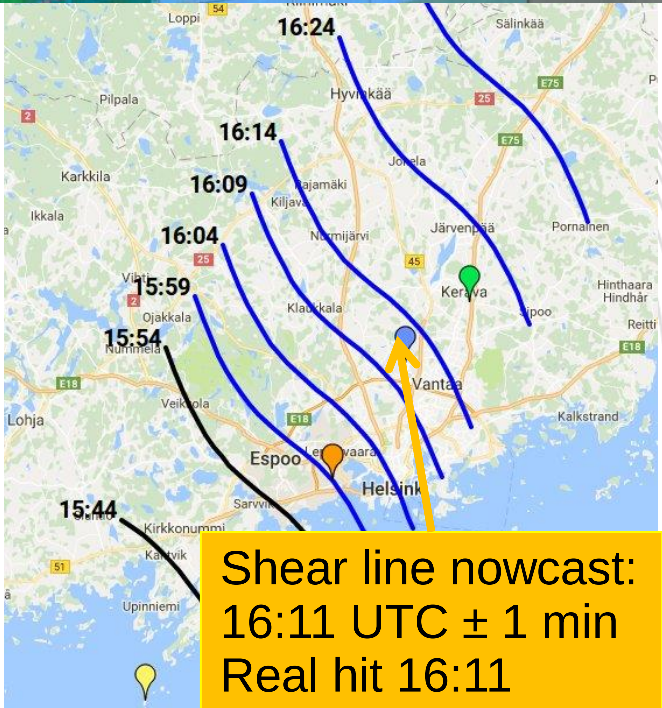
Uses of weather radars in aviation

Monitoring and nowcasting of weather hazards – signals from precipitation and insects

- **Wind shear (mostly horizontal)**
- **Hail**
- **Severe convective storms**
- **Rainfall and snowfall intensity**
- **Visibility in snowfall**
- **Rainfall and snowfall accumulation**

Monitoring and nowcasting of bird migration hazard (and insect hazard) – new emerging application





Does an insect hazard exist?

Kuva: Samuli Stenius

Source: Liikennelentäjä 3/2016

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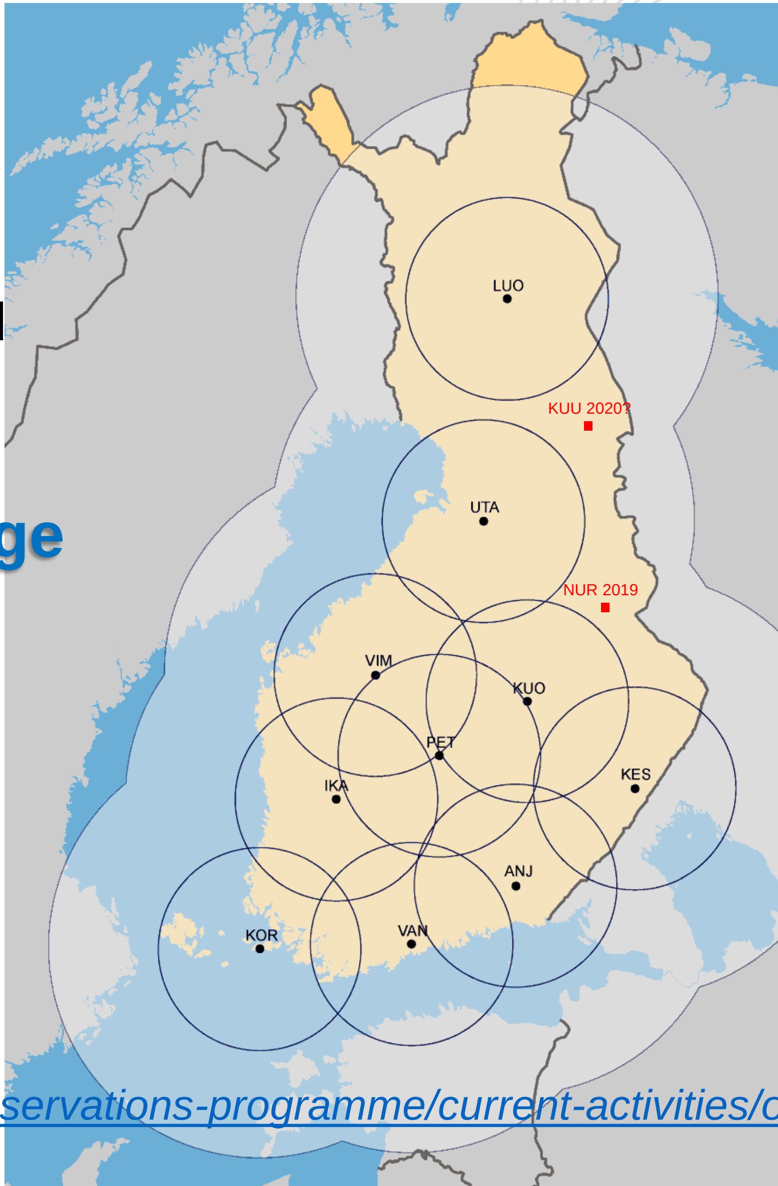
Weather radar networks

Vaisala HW&SW (RVP 900, IRIS)

In Finland

- 10 C-band Dual polarization radars
- System utilization rate >98 %
- ~10 TB/year (archived since 1998)



Radar data exchange

Nordic NWSs:
NORDRAD →
North European:
EU/Baltrad
http://baltrad.eu/

Pan-European:
EUMETNET/OPERA
http://eumetnet.eu/activities/observations-programme/current-activities/o

Weather radar data

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Conventional moments (commonly operational, less commonly, transmit horizontal polarization H).

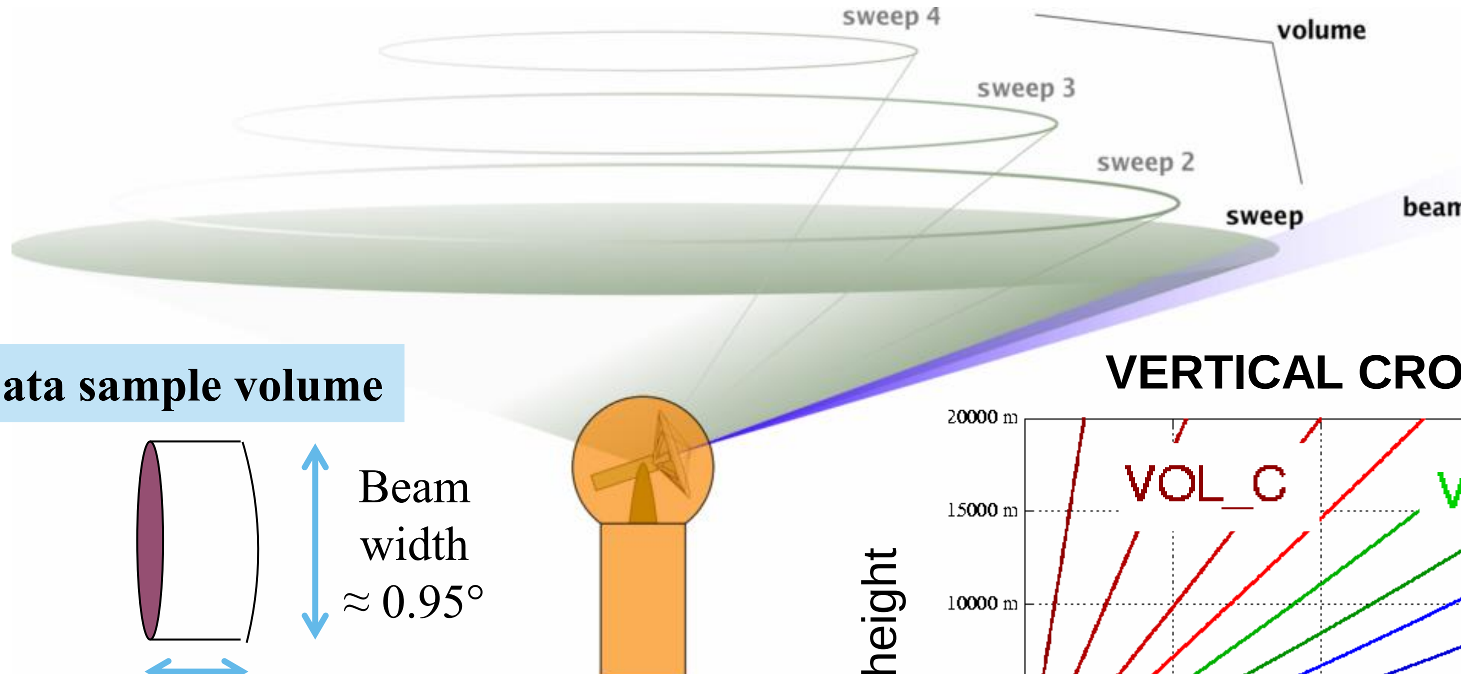
- **dBT, dBZ (radar reflectivity factor on a dB scale with and without ground clutter, typically -30 … +70 dBZ)**
- **SNR (signal to noise ratio)**
- **V (Doppler velocity), W (spectrum width), SQI (phase coherency)**

Dual polarization moments (transmit H&V, receive H&V)

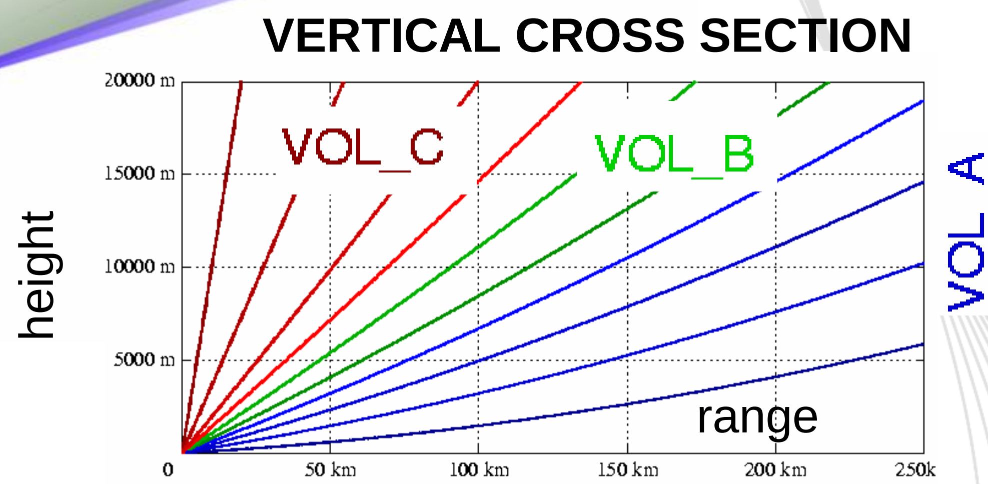
- **dBZE (enhanced reflectivity factor from H & V)**
- **ZDR, Differential Reflectivity (Factor)**
- **ρ_{HV} , (Copolar) Correlation Coefficient**
- **Φ_{DP} , Differential Phase (Shift)**
- **K_{DP} , Specific Differential Phase (Shift)**
- **LDR, Linear Depolarization Rate (transmit H, receive V)**

Each quantity adds a dimension to a data **sample. Note: Height (AGL) is always obtained for each sample.**

Collection of data samples - Scanning strategy



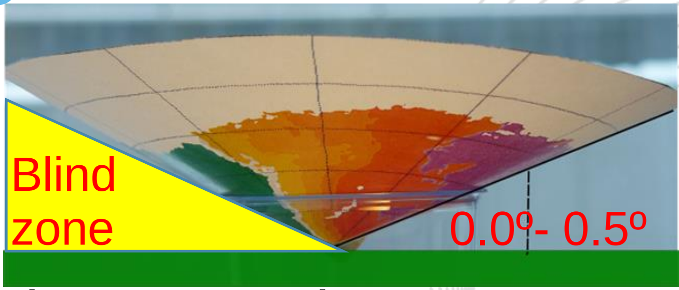
Data sample volume



- In a volume scan, the antenna rotates e.g. through the 2-4 lowest angles of elevation (VOL_A) every 5 minutes, and the higher 6-10 angles (VOL_B and VOL_C) every 15 minutes; each elevation consists typically of 360 azimuth rays. Note: The lowest elevation angle is typically 0.0 – 0.5 degrees.
- 500 - 2000 digital data samples (bins) along each ray between 0.5 – 250 km
- Volume scan ≈ 10 elevations x 360 azimuths x 500 ranges x 10 quantities

Data displays

“Slicing” of single radar volume data :



- PPI: quantity on a fixed elevation angle
- CAPPI: data at a fixed height, e.g. 500 m
- PsCAPPI or PseudoCAPPI: fixed height to the range where it can be reached, at longer ranges the lowest elevation PPI
- XSECT: vertical cross section along a line, calculated from 3D volume data
- TOP: height of echo top with preselected dBZ-threshold (e.g. -10 dBZ)
- MAX: maximum value at all vertical columns of all PPIs
- VVP or VAD, VPR, VPB: vertical soundings above the radar
- THVVP: time-height cross section of wind soundings
- “PREC”: instantaneous or accumulated precipitation

- RHI: fixed azimuth, antenna scans between elevations e.g. 0 - 90 ° => much better vertical resolution

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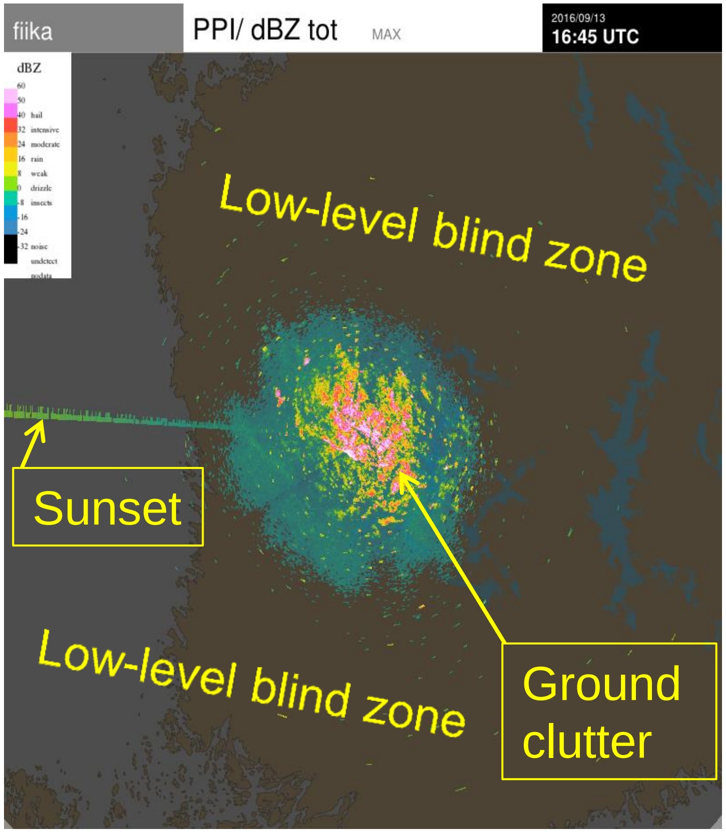
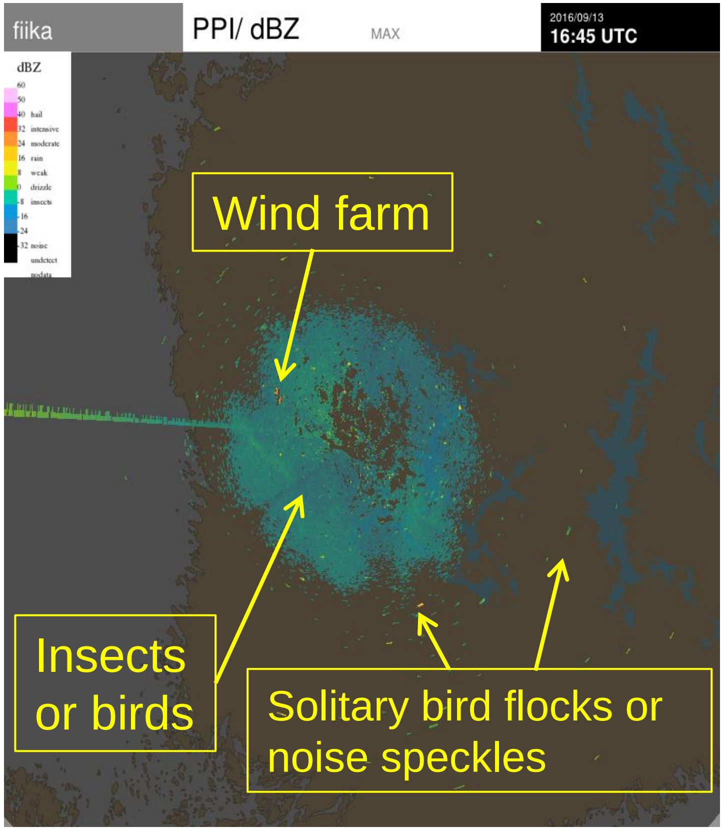
Data processing for optimal detection

Perform reasonable QC processing, e.g. Doppler-filtering for ground clutter rejection, dBT → dBZ



Perform reasonable post processing, e.g. fill the holes due to Doppler filtering utilizing MAX product instead of PPI



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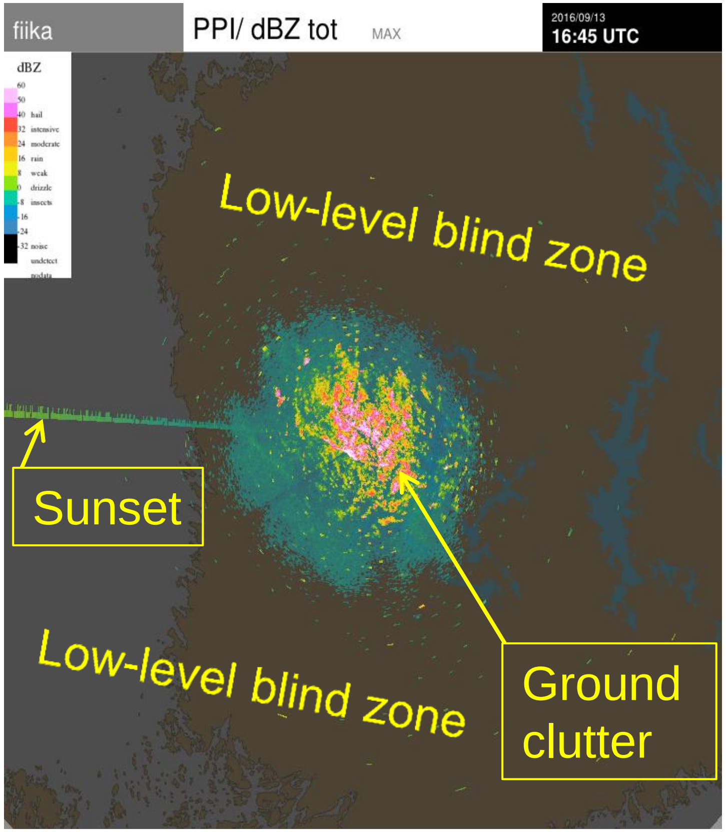

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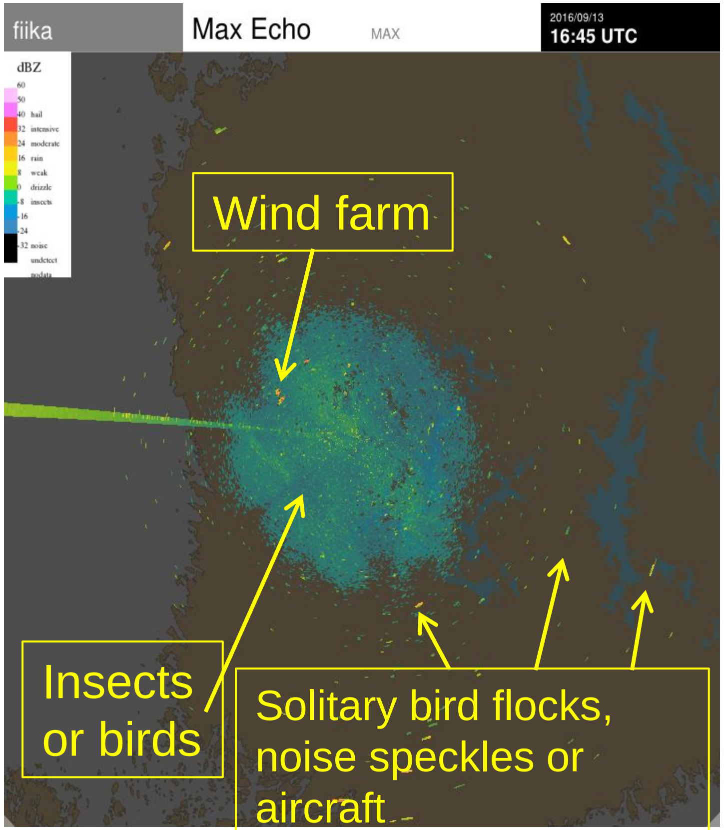


Radar equation for many distributed scatterers in the sample volume (precipitation, insects, birds)

$$\frac{P_r R^2}{LC|K|^2} = Z_e$$

- Z_e is effective (radar) reflectivity factor (dBZ = 10·logZ_e)
- P_r is the measured average power in Watts
- R is the measured distance from radar
- L is attenuation (atmosphere, radome, heavy rain, but is usually small)
- C is the radar constant for each particular radar system (set in the calibration)
- $|K|^2$ dielectric factor, depends on the scattering media

dBZ to bird density

radar reflectivity, dimensionally more well suited to flying animal density

dielectric constant for liquid water $|K|^2$ = 0.93

$$Z = 10^{(dBZ/10)}$$

$$\eta = \frac{\pi^5}{\lambda^4}|K|^2 Z$$

wavelength, λ = 0.1 m

- Then calculate the number of flying animals of a certain radar cross-section by cubic meter
- Number of birds in a given sample volume is computed by multiplying the number of birds per cubic meter by the number of cubic meters in the sample volume

$$N_{bio} = \frac{\eta}{\sigma}$$

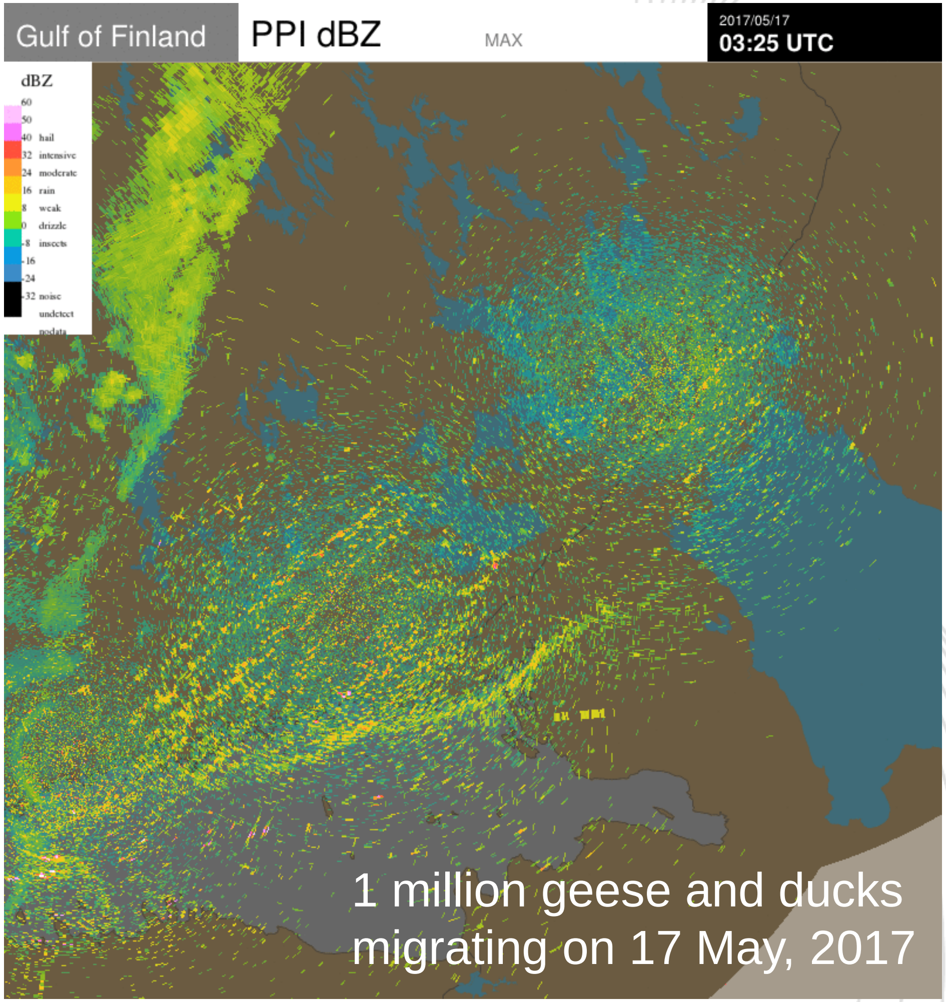
From insects to large birds, this can vary considerably in the sample volume

- When the sample contains many species $Z_e \approx$ (total animal mass)^2

- Numerous assumptions
- see Chilson et al. 2012, *Ecosphere*, for a full treatment

Weather radar validation with other sensors

- Visual bird counts and known phenology
- Moonwatching (e.g. Gauthreaux and Belser, 1998, Troesch et al. 2005)
- Dedicated bird radars (e.g. Dokter et al., 2011)
- Radar wind profilers (Weisshaupt et al. 2017, 2018)
- Thermal imaging (e.g. Weisshaupt et al. 2017; Zehnder et al. 2001)



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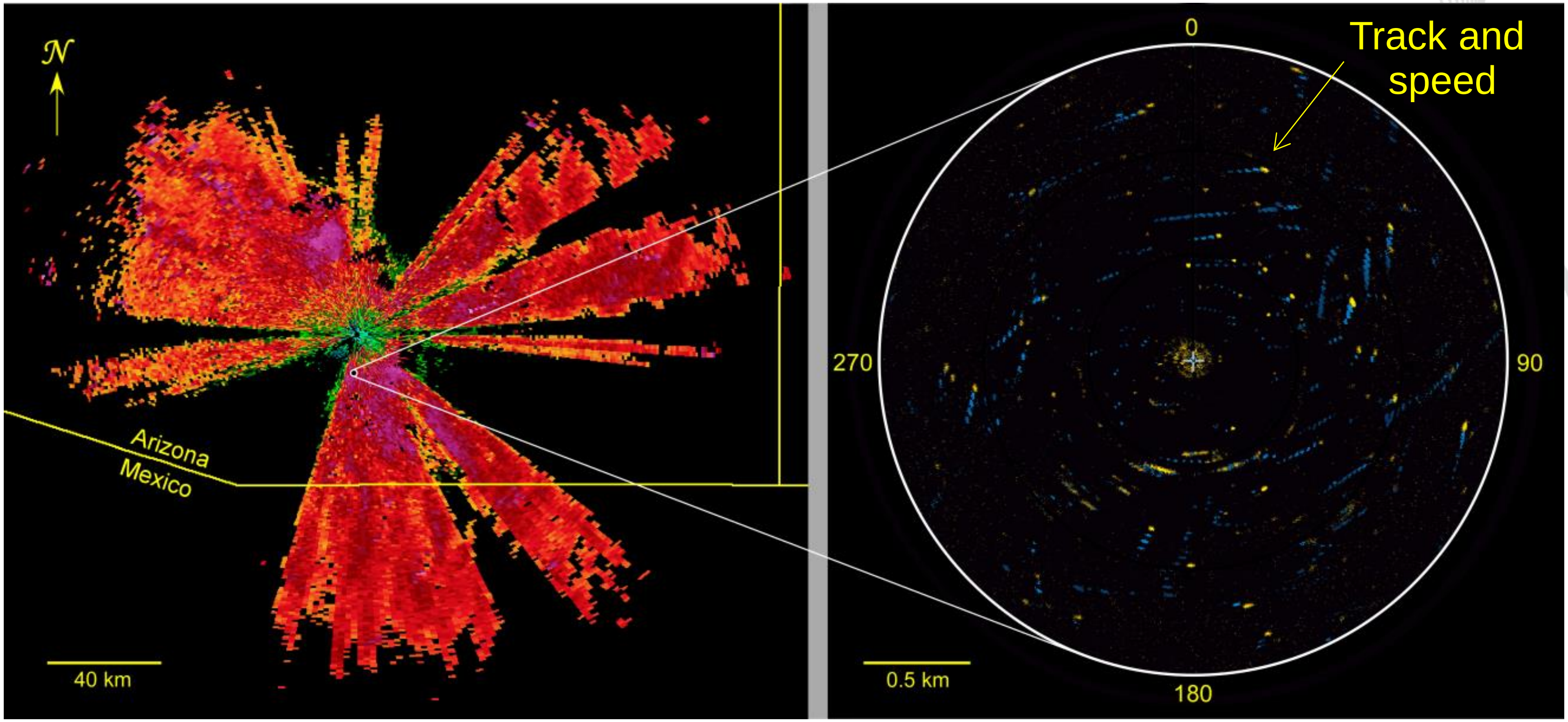
Note different spatial and temporal scales: The other tools detect locally but weather radars wider scale patterns and locally vertical distributions



Bridge et al. 2011, *BioScience*

Weather radar
Note blind sectors due to obstacles surrounding the antenna.

Bird radar

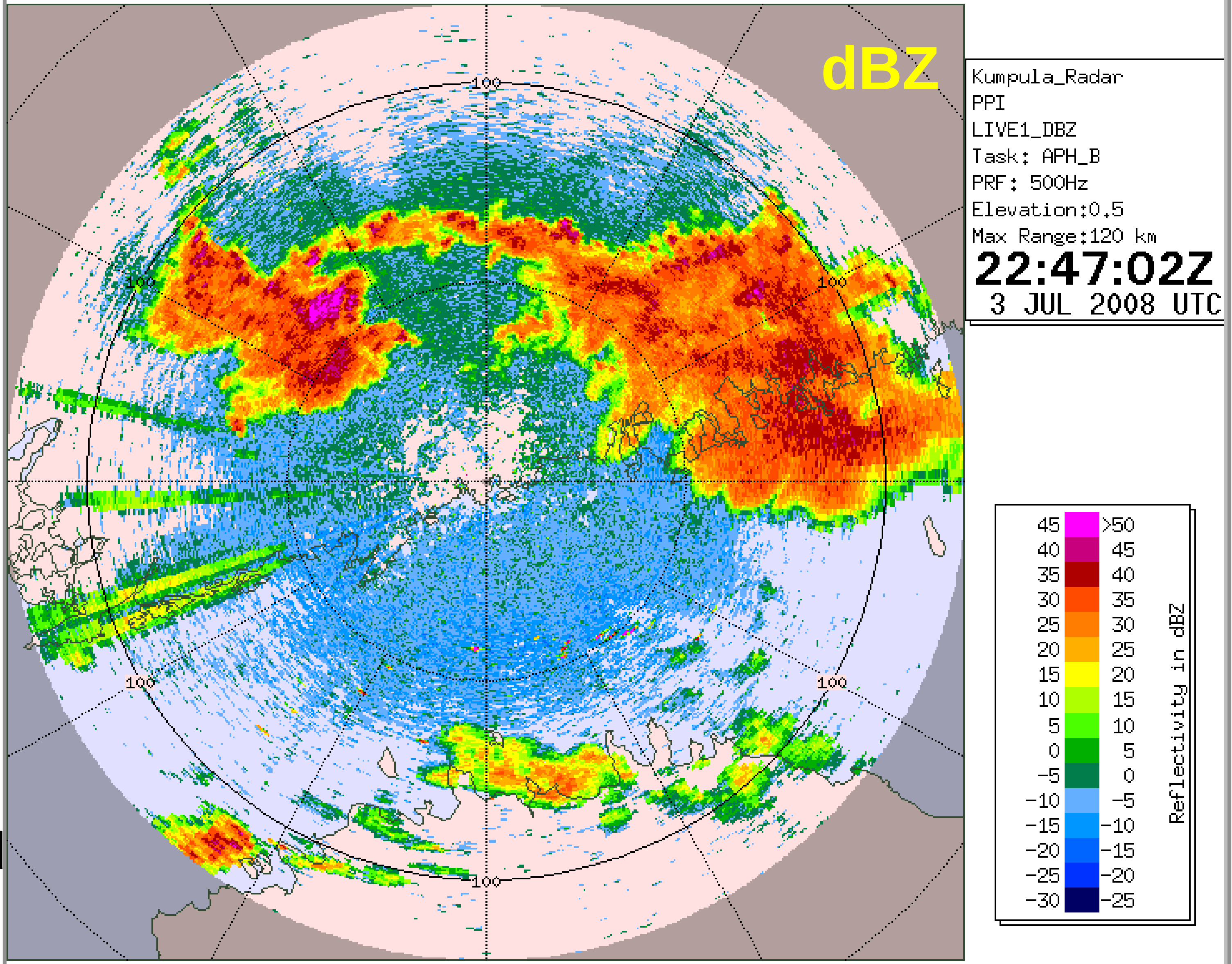
Example: dBZ (dBT & SNR)

Which phenomena?

- TS-rain
- reflections
- insects
- ships

How do we know?

- magnitude of measured quantities
- patterns and texture

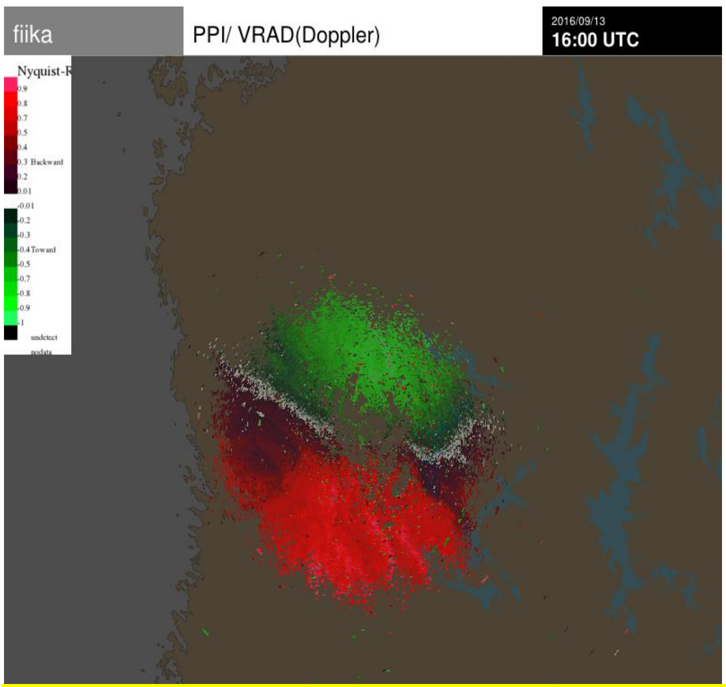


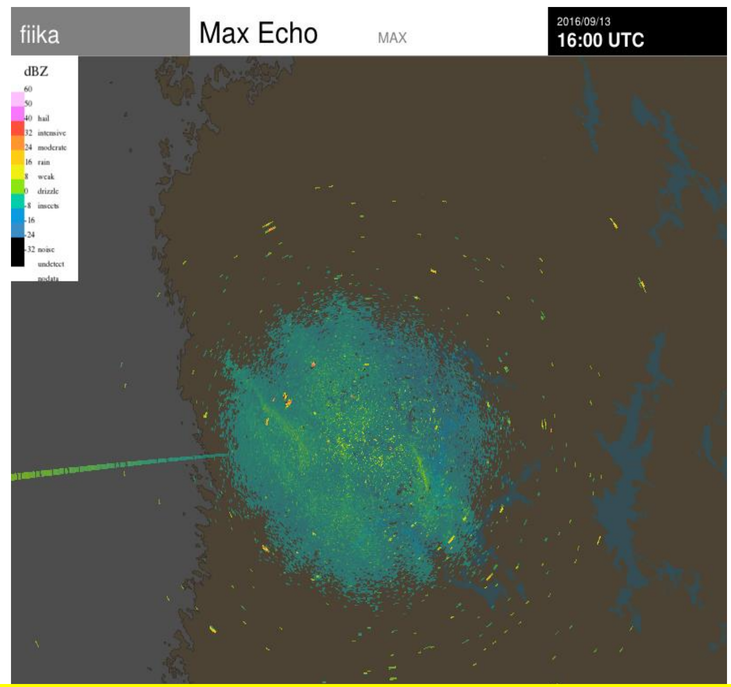
Example: Confirmed migration of insects (before 18 UTC) and nocturnal passerines (thereafter)

Perform classification of the phenomenon utilizing Doppler velocity (**V**) and its variance (**σ^2V**) and dual pol moments

Typical ”clean” nocturnal passerine migration outburst:

- Starts abruptly ~1 hour after sunset
- Gains altitude as a roundish annulus



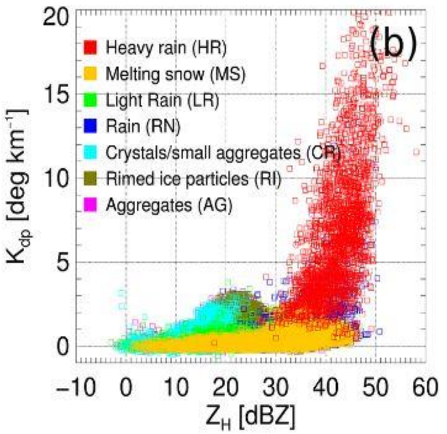


Manual classification is slow and not easy.The need is for sample volume -based automatic classification – fast but not yet well established

Minimum number of separable classes

METEOROLOGICAL
- Drizzle, snow grain
- Rain
- Dry snow
- Wet snow
- Attenuated precipitation
- Graupel
- Hail

It is relatively easy to obtain independent measured reference data ~*in situ* for clustering analysis, e.g. Grazioli et al. 2015: Atmos. Meas. Tech.



BIOLOGICAL
- **Birds**
- **Insects**

A further need exists for subtypes of biological scatterers

OTHERS
- Regular and anomalous ground clutter - implicitly done in the DSP – not with **wind farms**!
- **Aircraft & ships**
- **Noise speckles**
- **Regular and anomalous sea clutter**
- **Chaff**
- **Anthropogenic microwave emitters and the sun**
- **Specular reflections**
- **Second trip echoes**

It is uncommon to obtain independent operationally measured reference data ~*in situ*

We need:
- Supervised *a priori* classes or
- Expert-based class naming after automatic clustering

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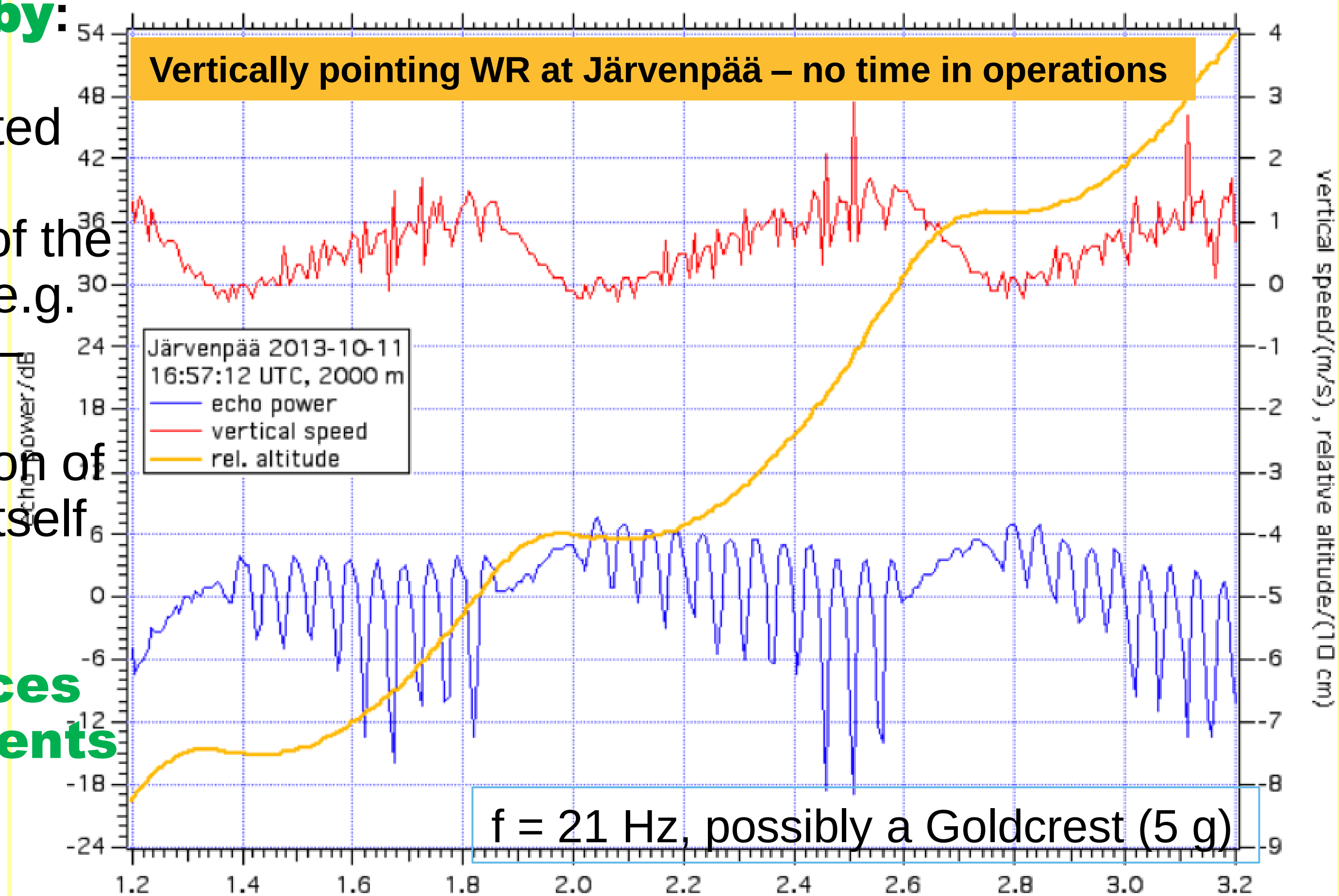
Benefits of automatic classification

Improved quality and accuracy of meteoro-logical products by:

- Filtering of unwanted features
- Better estimation of the physical situation,e.g. $R,S(K_{DP}, ZDR, Z_e)$ – conversions
- Improved calibration of the radar system itself (ZDR)

Ecosystem services of animal movements

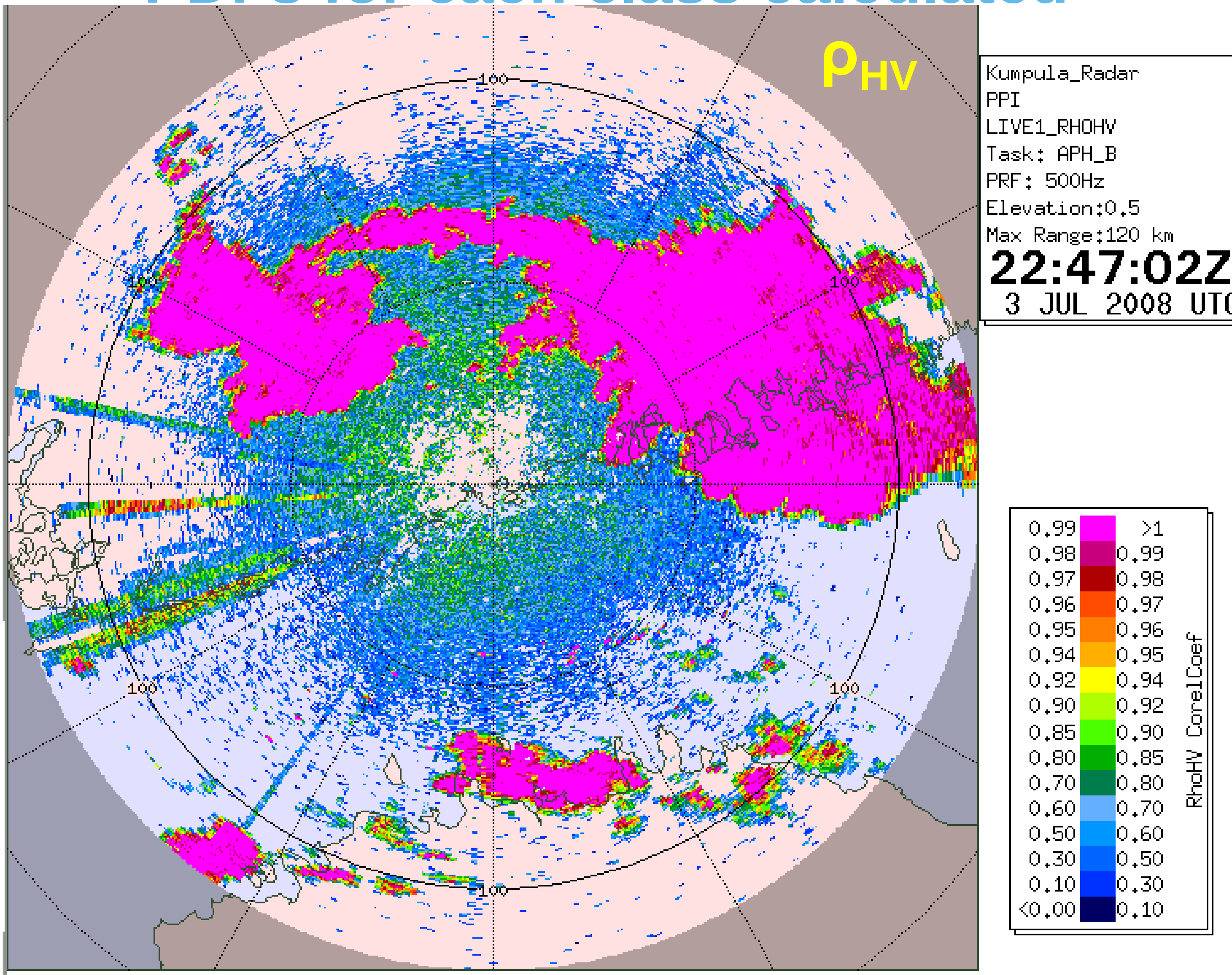


http://www.cost.eu/domains_actions/essem/Actions/ES1305, http://www.enram.eu/
Shamoun-Baranes et al. 2014: Movement Ecology 2:9; Zübeyde Gürbüz et al. 2015: Proceedings, IEEE Radar Conf.

Probabilistic classification: separating measured and texture quantities and their PDFs for each class calculated

PDFs of separating quantities => Probabilistic classification of the target => Quality thresholds according to each customer application

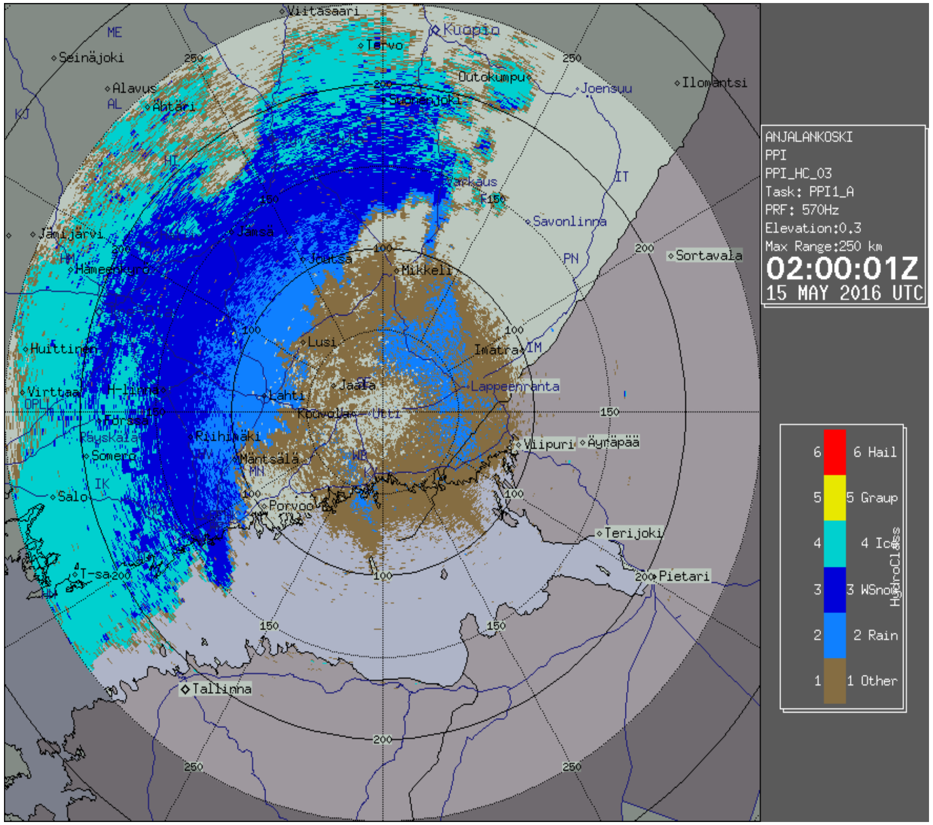
All information can be valuable – Apply filtering in the product, not in the measurement!



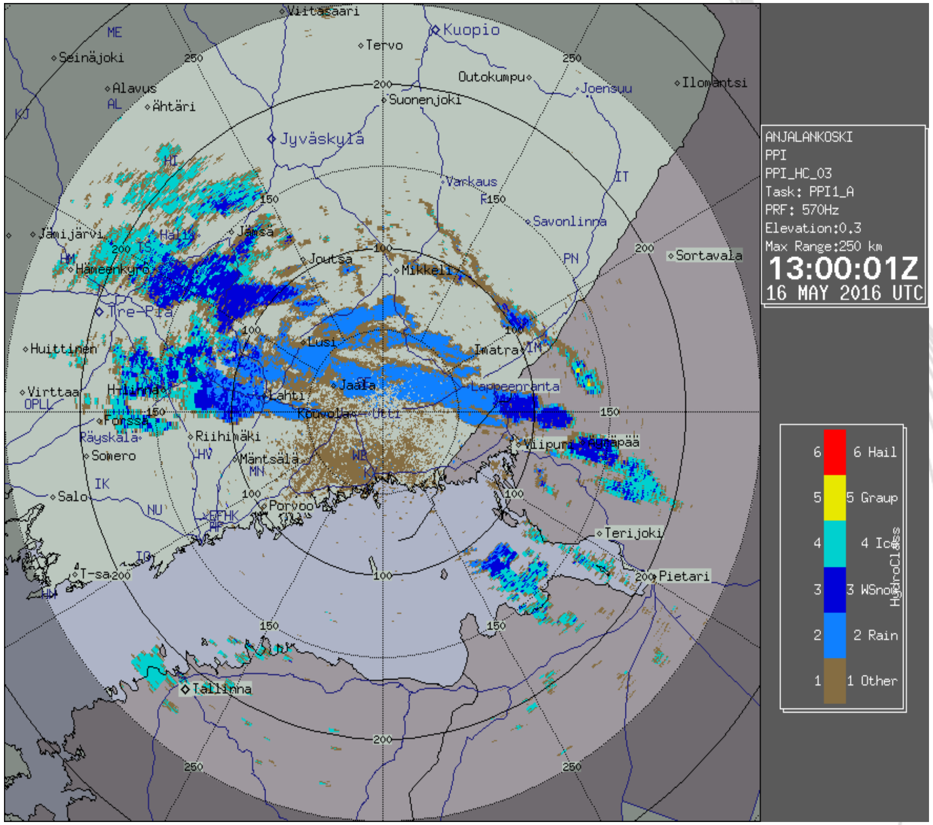
Method: Fuzzy logic classification

- **Available for hydrometeor types** (e.g. Straka et al., 2000) **emerging for other scatterers** (e.g. Peura and Koistinen, ERAD 2016)
- Below: The Vaisala HydroClass™ separates non-meteorological bins as a joint class – not perfectly well (see also Lakshamanan et al. 2013)

Insects (aphids) on 15 May 2016



Birds (and insects) on 16 May 2016



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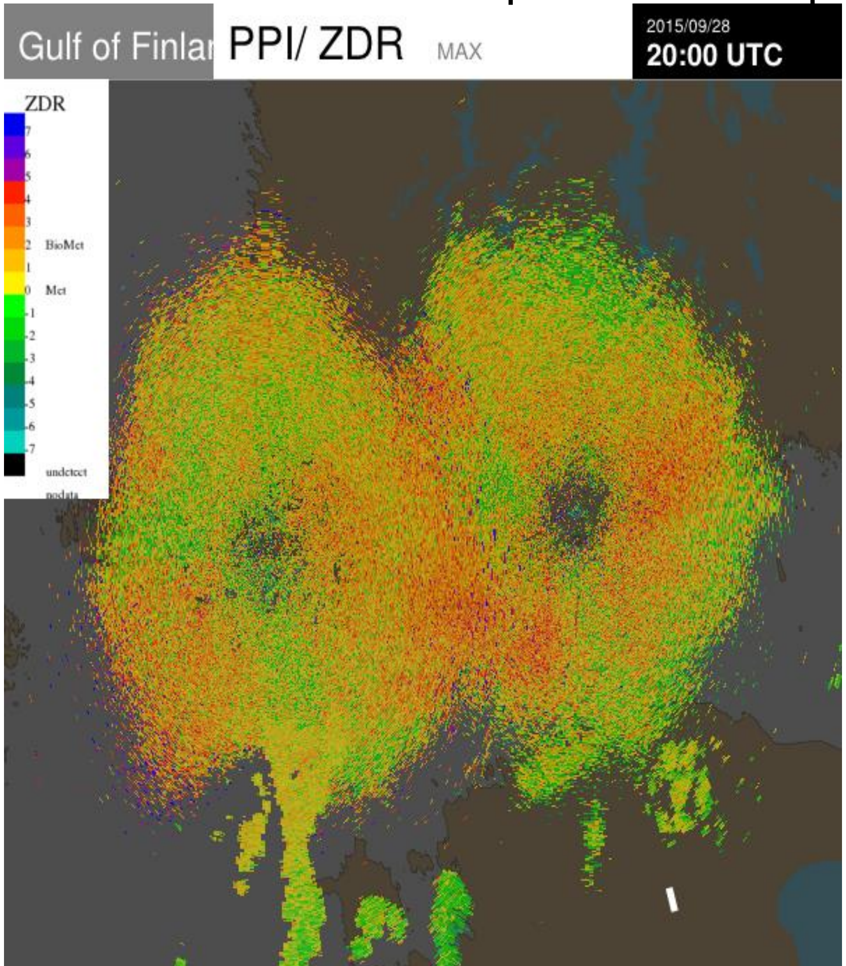
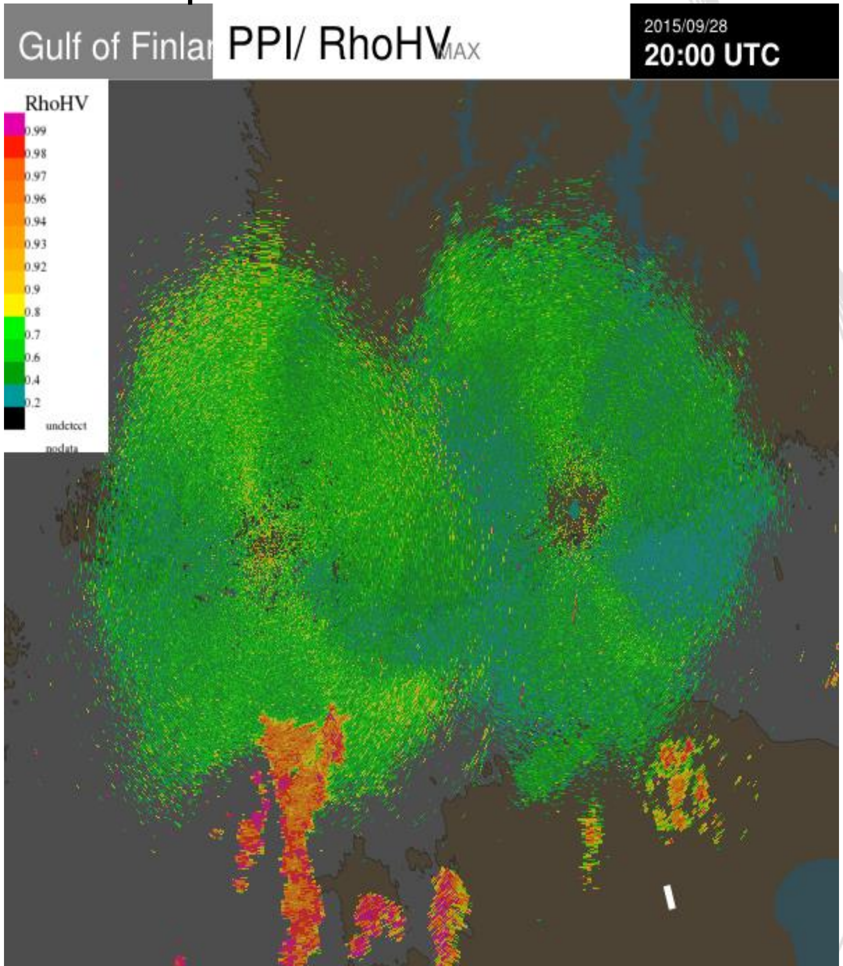
Modeling of training data PDFs

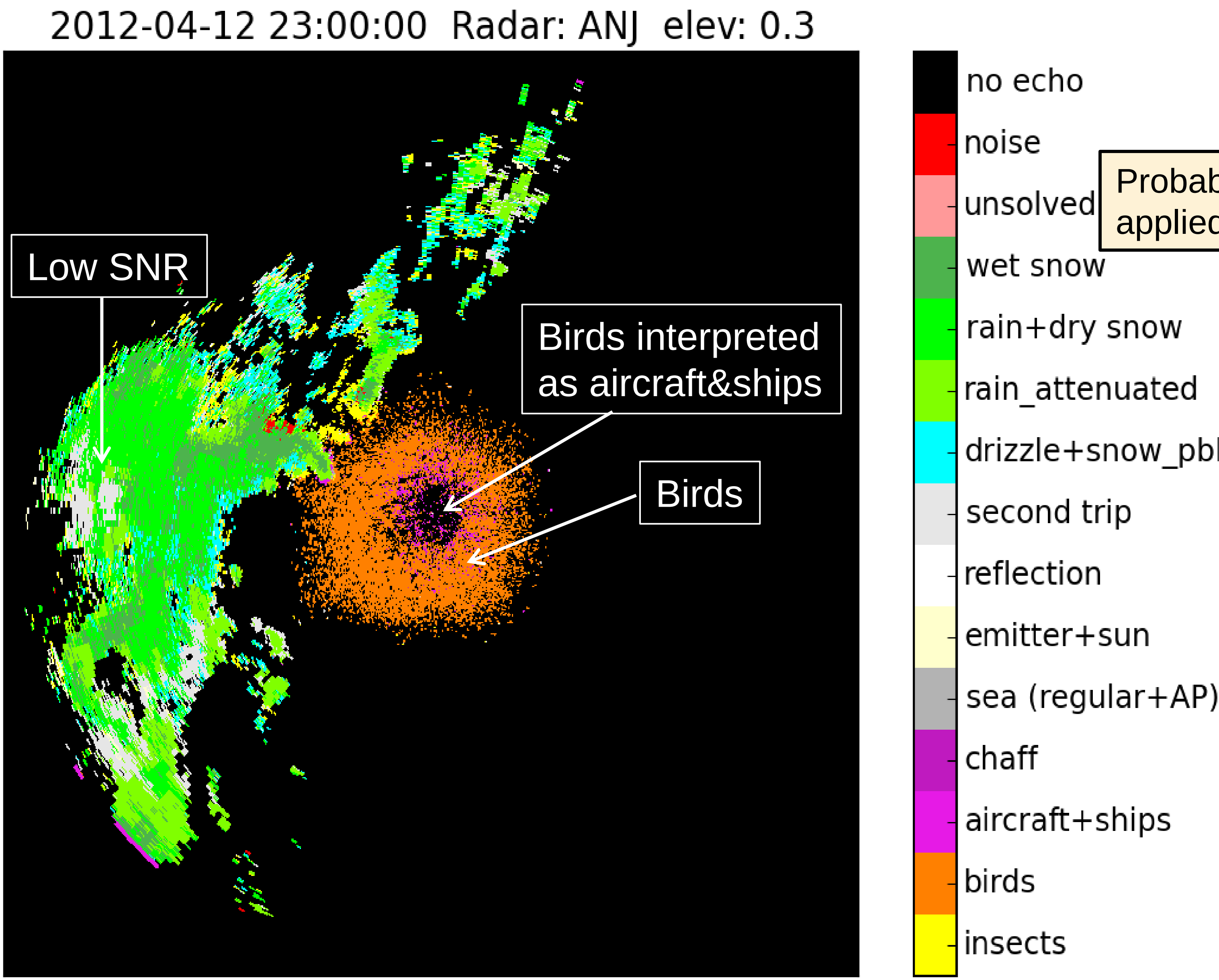
- Principal component analysis, PCA (has serious limitations)
- Orthogonal polynomial transfer OPT
- Naive or ”ultra-naive” Bayesian classification

Case example: nocturnal passerines on polarimetric radars



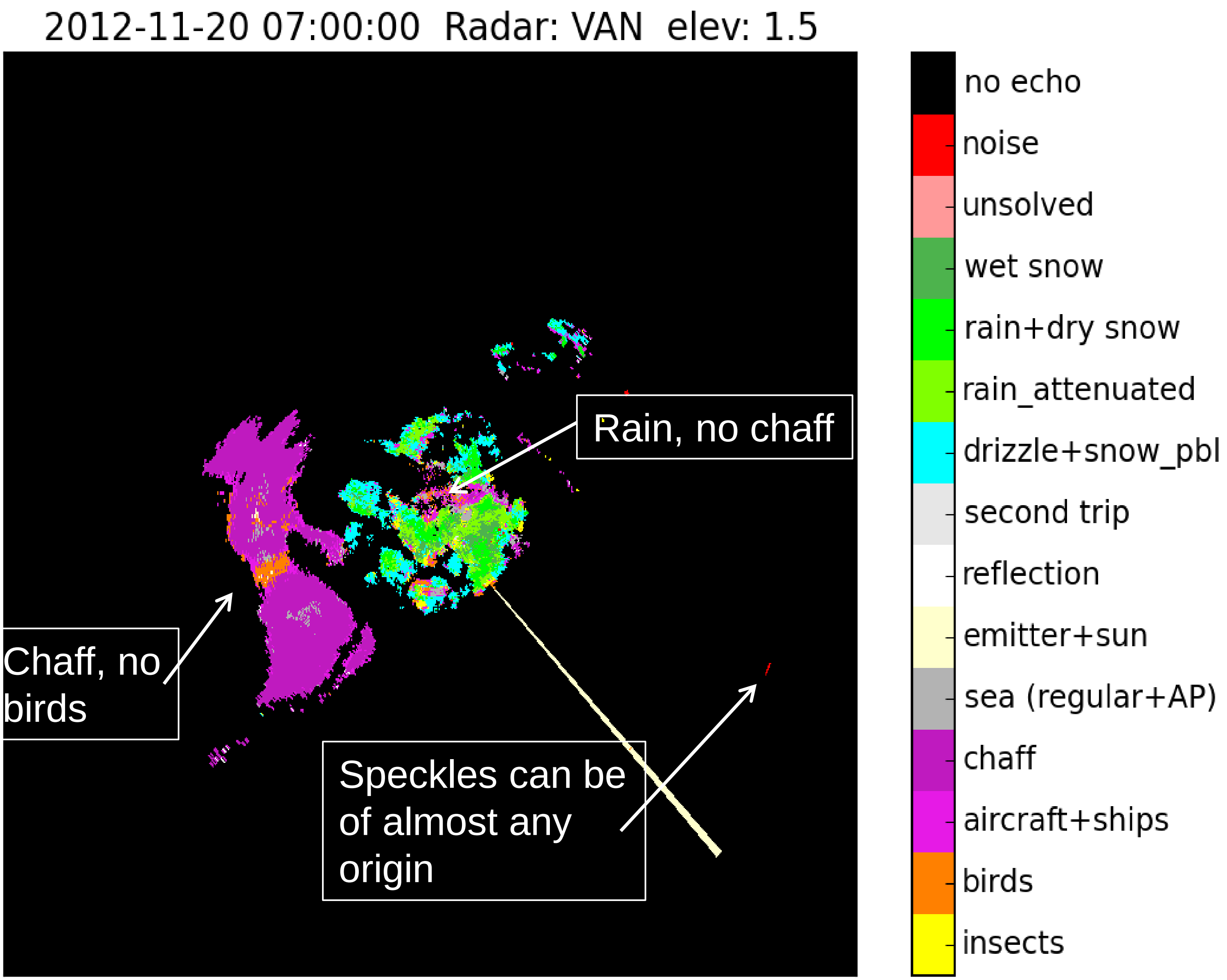


Rain and nocturnal birds



Probability threshold not applied in this image

Rain, chaff and the sun



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Conclusions

- Weather radars…
  - Detect well dispersed nocturnal and morning passerine migration.
  - Have somewhat limited potential for detection of concentrated streams of diurnal migration (waterfowl, waders, soaring migrants).
  - Cannot separate/track speckle-like patterns (noise, aircraft, solitary bird flock, ship)
  - Are good for large-scale monitoring migration, not good for warning of individual flocks.
- Doppler and polarimetric data and external weather information: useful for proper and automatic recognition of target classes.
- Automatic classifications emerging, should be probabilistic.
- Potential H2020 funding for radar-based quantitative migration model at FMI.