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   Parametric turbulence model

3 Simulation of radar observables
   Zephyros

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   Staring radar
   Polarimetric radar spectra
   Canting angles
   Inertia effect

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Ultra Fast wind SensOrs project

The UFO project

A solution to mitigate weather hazards and increase airport capacity.

Prospect: WVs and weather hazards can be monitored under all weather conditions by using UFO scanning radars and lidars!!
Research question

How does turbulence look like from the radar?

1. How can turbulence models be used for simulation of radar measurements?
2. How does turbulence look like in polarimetric radar measurements?
3. How to optimize turbulence intensity remote sensing?
The problem with radar turbulence retrievals

\[
\sigma_v^2 = \sigma_d^2 + \sigma_0^2 + \sigma_\alpha^2 + \zeta I \sigma_T^2
\]

Assumption of homogeneous isotropic turbulence

- **light turbulence**
  \[\zeta I \sigma_T^2 \ll \sigma_d^2, \sigma_0^2, \sigma_\alpha^2\]
- **moderate turbulence**
  \[\zeta I \sigma_T^2 \propto \sigma_d^2, \sigma_0^2, \sigma_\alpha^2\]
- **strong turbulence**
  \[\zeta I \sigma_T^2 \gg \sigma_d^2, \sigma_0^2, \sigma_\alpha^2\]

- **small footprint**
  \[\zeta = ?\]
- **large footprint**
  \[\zeta = 1\]

- **turbulence too small to measure**
- **turbulence intensity**
- **turbulence intensity**
- **turbulence intensity**
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Overview of turbulence models

Stochastic turbulence models
- Random initialization.
- With given parameters, the outcome is always different.
- Different applications and complexity.

Parametric turbulence model
- With the given parameters, the outcome is always the same.
- Very artificial.
Stochastic turbulence models

Figure: Schematic overview of turbulence models.
Stochastic turbulence models

Example (Careta and Sagues (1993))

- Start from auxiliary random scalar, which is transformed to a divergence free 2D field.
- Used for study of diffusion processes.
Stochastic turbulence models

Example (Mann (1998))

- 3D wind field, spectral tensor is used.
- Used in wind engineering.
Stochastic turbulence models

Example (Pinsky and Khain (2006))

• 2D windfield, obeys the continuity equation
• Used for simulation of diffusion processes
Stochastic turbulence models

Example (Oude Nijhuis et al. (2014))

- 1D windfield, large dynamic range (mm-km scale)
- Used for turbulence intensity retrieval studies.
Parametric turbulence models

Defining parameter: turbulence broadening $\sigma_T$, which depends on turbulence intensity, $\epsilon$, and the radar resolution volume parameters.

Solutions to integrate it in the radar measurements:

1. Smearing/smoothening/broadening of spectra. [typical approach, not considered]
2. Ensemble of isotropic vectors.
For each particle, an ensemble of isotropic vectors is used:

\[ \vec{v}_{p,*} = \vec{v}_{\text{terminal}} + \vec{v}_{\text{air}} + \vec{v}_{\text{turbulence,*}}, \]  

(1)

where for each 3D unit direction \( \hat{k}_* \),

\[ v_{\text{turbulence,*}} = \sigma_T \sqrt{3} \hat{k}_*. \]  

(2)

The average cross section is obtained by averaging over all directions:

\[ \overline{\sigma} = \frac{1}{n} \sum \sigma(\vec{v}_{p,*}). \]  

(3)

- The particle symmetry axis (minor axis) is parallel to \( v_{p,*} \).
- Canting angle distribution is implicitly modelled.
Parametric turbulence models

Ensemble of isotropic vectors

For each particle, an ensemble of isotropic vectors is used:

\[
\vec{v}_{p,*} = \vec{v}_{\text{terminal}} + \vec{v}_{\text{air}} + \vec{v}_{\text{turbulence,*}},
\]

(4)

<table>
<thead>
<tr>
<th></th>
<th>0.1 mm</th>
<th>1.0 mm</th>
<th>5.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>light turbulence,</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sigma = 0.1 \text{ ms}^{-1} ).</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>heavy turbulence,</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sigma = 2.0 \text{ ms}^{-1} ).</td>
<td><img src="image4.png" alt="Diagram" /></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
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</tbody>
</table>
### Overview of turbulence models

<table>
<thead>
<tr>
<th>Reference</th>
<th>Application</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA93</td>
<td>Diffusion processes</td>
<td>2D</td>
</tr>
<tr>
<td>MA98</td>
<td>Wind turbine engineering</td>
<td>3D</td>
</tr>
<tr>
<td>PI06</td>
<td>Droplet tracks</td>
<td>2D</td>
</tr>
<tr>
<td>CTM14</td>
<td>EDR retrievals</td>
<td>1D, scale symmetric</td>
</tr>
<tr>
<td>PA15</td>
<td>Radar observables</td>
<td>No field simulation.</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Reference</th>
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</thead>
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<tr>
<td>PA15 (ensemble of isotropic vectors)</td>
<td>Radar observables</td>
<td>No field simulation.</td>
</tr>
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</table>

**Table:** Selection of turbulence models.
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Zephyros

- Zephyros is a software package under development for wind/turbulence simulation and retrieval.
- Development version publicly available on GitHub.
- Written mostly in C, bit of Fortran. Interfaces for Python/Matlab.
- Has fast mode for retrievals (small ensemble of scatterers) and slow mode (large ensemble, better accuracy) for simulations.
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Scanning radar

Details of the simulation

- Radar scans in the xy-plane.
- No noise is added.
- Frequency 3.298 GHz radar (S-Band)
- EDR = 0.1 m²s⁻³. (very strong turbulence!)
- LWC = 1 gm⁻³, rain with gamma distribution parameters, \( \mu = 5, D_0 = 2\text{mm} \).
- Resolution volume parameters, FWHM = 2.1 °, range resolution 30 m.
Scanning radar

Doppler mean velocities

CA93

MA98

PI06

CTM14

PA15

light turbulence, \( \sigma = 0.1 \text{ ms}^{-1} \).

heavy turbulence, \( \sigma = 2.0 \text{ ms}^{-1} \).
Scanning radar

Doppler spectral width

CA93

MA98

PI06

CTM14

PA15

light turbulence, \( \sigma = 0.1 \text{ ms}^{-1} \).

heavy turbulence, \( \sigma = 2.0 \text{ ms}^{-1} \).
Staring radar

Details of the simulation

- Radar **stares** along the $x$ line.
- No noise is added.
- Frequency 3.298 GHz radar (S-Band)
- $EDR = 0.1 \text{ m}^2\text{s}^{-3}$. (very strong turbulence!)
- $LWC = 1 \text{ gm}^{-3}$, rain with gamma distribution parameters, $\mu = 5, D_0 = 2\text{mm}$.
- Resolution volume parameters, $FWHM = 2.1^\circ$, range resolution 30 m.
Staring radar

Doppler spectra for hh

CA93

MA98

PI06

CTM14

PA15

light turbulence,
$\sigma = 0.1$ ms$^{-1}$.

heavy turbulence,
$\sigma = 2.0$ ms$^{-1}$.
Polarimetric radar spectra

Details of the simulation

- Radar stares at 45° in the xz-plane.
- No noise is added.
- Frequency 3.298 GHz radar (S-Band)
- EDR is varied in the simulations.
- LWC = 1 gm⁻³, rain with gamma distribution parameters, \( \mu = 5, D_0 = 2\text{mm} \).
- Range is 1 km, resolution volume parameters: FWHM = 2.1°, range resolution 30 m.
Polarimetric radar spectra

Polarimetric variables for Mann (1998)

<table>
<thead>
<tr>
<th>$\epsilon$ [m$^2$s$^{-3}$]</th>
<th>$10^{-5}$</th>
<th>$10^{-2}$</th>
<th>$10^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{v, hh}$ [ms$^{-1}$]</td>
<td>0.750</td>
<td>0.802</td>
<td>9.67</td>
</tr>
<tr>
<td>$dBZdr$</td>
<td>0.601</td>
<td>0.631</td>
<td>0.668</td>
</tr>
<tr>
<td>$dBBLdr$</td>
<td>-67.3</td>
<td>-46.0</td>
<td>-37.7</td>
</tr>
</tbody>
</table>

- Zdr, Ldr and spectral width contain turbulence intensity information.

$$< Z_{DR} >= dB(< \eta_{hh} > / < \eta_{vv} >)$$  (5)

$$< L_{DR} >= dB(< \eta_{hv} > / < \eta_{vv} >)$$  (6)
Polarimetric radar spectra

Polarimetric variables for the parametric model

<table>
<thead>
<tr>
<th>Variable</th>
<th>10^{-5}</th>
<th>10^{-2}</th>
<th>10^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon$ [m$^2$s$^{-3}$]</td>
<td>10^{-5}</td>
<td>10^{-2}</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>$\sigma_{v,hh}$ [ms$^{-1}$]</td>
<td>0.750</td>
<td>0.847</td>
<td>1.14</td>
</tr>
<tr>
<td>dBZdr</td>
<td>0.597</td>
<td>0.589</td>
<td>0.555</td>
</tr>
<tr>
<td>dBLLdr</td>
<td>-63.5</td>
<td>-43.2</td>
<td>-36.4</td>
</tr>
</tbody>
</table>

- Parametric model reproduces the same dependencies as the stochastic model!

\[
< Z_{DR} > = dB\left( < \eta_{hh} > / < \eta_{vv} > \right) \quad (7)
\]
\[
< L_{DR} > = dB\left( < \eta_{hv} > / < \eta_{vv} > \right) \quad (8)
\]
Polarimetric radar spectra

hh Doppler spectrum

MA98

PA15
Polarimetric radar spectra

specific Zdr

MA98

PA15
Polarimetric radar spectra

specific Ldr

MA98

PA15
Canting angles

canting angle spread

MA98

PA15

Experiment

- Right figure from Beard et al. (2010).
Inertia effect

Solution

The inertial velocity term $\vec{v}''_p$ is assumed to be small in comparison to the total particle velocity:

$$\vec{v}_p = \vec{v}_{\text{terminal}} + \vec{v}_{\text{air}} + \vec{v}'_p$$  \hspace{1cm} (9)

The solution is found by solving the equations of motion for a backward small trajectory:

$$\frac{dv_{p,z}}{dt} = F_g - F_b - F_{d,z} = \eta_{l,z}v_t^2 - \eta_{l,z}(v_{p,z} - v_{a,z})^2.$$  \hspace{1cm} (10)
Inertia effect

Solution

\[ \mu = 5, \quad \epsilon = 10^{-2} \]

\[ \mu = 5, \quad D_0 = 5 \text{ mm} \]

**simulation of inertia** Doppler spectral width with (striped) and without (line) the inertia effect.
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Conclusions

- Zdr and Ldr contain information on the turbulence intensity, which can be used in turbulence retrievals in precipitation. It depends however on the DSD.
- The inertia effect can alter the Doppler spectral width.
- A parametric model is found that can reproduce the features of radar measurements for stochastic turbulence.
- The parametric model implicitly reproduces the canting angle distribution.
References


The end

Thank you for your attention

Questions?
### Radar filter

1. **User input**: drop size distribution, atmospheric temperature profile, parameters that characterize the radar.

2. **Dividing resolution volume in subvolumes**: The resolution volume is divided into equally weighted subvolumes.

3. **Coordinate transformations**: BEAM $\rightarrow$ AZEL $\rightarrow$ ENU.

4. **Interpolation of user input**: For each subvolume, the user input that is required is interpolated.

5. **Radar cross sections**: are calculated for each subvolume and for each particle.

6. **Radar observables**: are calculated according to their definitions.
Radar filter

The weather radar equation can be written as (details → Doviak and Zrnic (2006)):

\[
\langle P_*(r_0) \rangle = \frac{C_r}{r_0^2} \eta_*,
\]  

(11)

where \( \langle P_* \rangle \) is the expected received power, \( C_r \) a radar constant, \( r_0 \) the range at the resolution center and \( \eta_* \) the reflectivity. The reflectivity, \( \eta_* \) is defined as:

\[
\eta_* = \int_{\Omega} \sigma_*(D_e) N(D_e) dD_e,
\]

(12)

(13)
### Radar filter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar reflection factor</td>
<td>$\langle \eta_* \rangle = \sum_i \frac{\eta_{*,i}}{n}$</td>
</tr>
<tr>
<td>Reflectivity factor</td>
<td>$\langle Z_* \rangle = 10 \cdot \log_{10} \left( \frac{\lambda^4}{\pi^5</td>
</tr>
<tr>
<td>Doppler velocity</td>
<td>$\langle v_{<em>,D} \rangle = \sum_i \frac{\eta_{</em>,i}}{n} v_{D,i} / \langle \eta_* \rangle$</td>
</tr>
<tr>
<td>Doppler spectral width</td>
<td>$\langle \sigma_{v,<em>,D}^2 \rangle = \sum_i \frac{\eta_{</em>,i}}{n} (v_{D,i} - \langle v_{<em>,D} \rangle)^2 / \langle \eta_</em> \rangle$</td>
</tr>
<tr>
<td>Differential reflectivity</td>
<td>$\langle Z_{DR} \rangle = 10 \cdot \log_{10} (\langle \eta_{hh} \rangle / \langle \eta_{vv} \rangle)$</td>
</tr>
<tr>
<td>Depolarisation ratio</td>
<td>$\langle L_{DR} \rangle = 10 \cdot \log_{10} (\langle \eta_{hv} \rangle / \langle \eta_{vv} \rangle)$</td>
</tr>
</tbody>
</table>
Backup slides: Radar filter

Radar filter

| Copolar correlation coefficient | \( < \rho_c > = \frac{\sum_i S_{hh,i} S_{vv,i}^\dagger}{\sqrt{\sum_i |S_{hh,i}|^2 \sum_i |S_{vv,i}|^2}} \) |
| Cross polar correlation coefficient | \( < \rho_{cx}^h > = \frac{\sum_i S_{hh,i} S_{hv,i}^\dagger}{\sqrt{\sum_i |S_{hh,i}|^2 \sum_i |S_{hv,i}|^2}} \) |
| | \( < \rho_{cx}^v > = \frac{\sum_i S_{vv,i} S_{vh,i}^\dagger}{\sqrt{\sum_i |S_{vv,i}|^2 \sum_i |S_{vh,i}|^2}} \) |
Backup slides: Radar filter

Radar filter

| specific differential phase | $\langle K_{DP} \rangle = 10^3 \lambda \left\{ \int_0^\infty \text{Re}(S_{hh}^f - S_{vv}^f)N(D_e)dD_e \right\} $ |
### Radar filter, spectra

<table>
<thead>
<tr>
<th>Doppler spectrum</th>
<th>$&lt; \eta_{<em>,1,2} &gt; = \sum_{i,v_1&lt;v_D,i&lt;v_2} \frac{\eta_{</em>,i}}{n} / (v_2 - v_1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific differential reflectivity</td>
<td>$&lt; Z_{DR,1,2} &gt; = 10 \cdot \log_{10}(&lt; \eta_{hh,1,2} &gt; / &lt; \eta_{vv,1,2} &gt;)$</td>
</tr>
<tr>
<td>specific depolarization ratio</td>
<td>$&lt; L_{DR,1,2} &gt; = 10 \cdot \log_{10}(&lt; \eta_{hv,1,2} &gt; / &lt; \eta_{vv,1,2} &gt;)$</td>
</tr>
<tr>
<td>specific correlation coefficients</td>
<td>$&lt; \rho_{1,2} &gt; = &quot; \cdots \cdots &quot;$ for $v_1 &lt; v_D, i &lt; v_2$</td>
</tr>
</tbody>
</table>