Assimilation of Attenuated Data From X-Band Network Using Ensemble Kalman Filter

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Advantages of X-band radar network

- Low cost
- High spatial and temporal resolutions
- Low level scan to fill in the gaps exist in current WSR-88D radar network
- Dense overlapping coverage
- Dynamically-adaptive scanning
  
  e.g. Center for Collaborative Adaptive Sensing of the Atmosphere (CASA)

Issues of using X-band radar data

- Attenuation correction is a significant area of research in QPE using reflectivity observations from X-band and other shorter-wavelength radars
- In traditional approach, attenuated observation is corrected in observation space, before data assimilation. (H-B solutions; Dual-polarization measurements; Dual-frequency observations)
- The traditional approaches can be effective only when the reflected power is above the noise floor of the radar receiver.
Modern data assimilation techniques such as variational and ensemble Kalman filter (EnKF) approaches are able to assimilate observations directly using the forward observation operators that link the model state variables to observations (Kalnay 2002).

Accurate observation operators should take into account radar beam propagation (Gao et al. 2006), beam pattern weighting (Xue et al. 2006; Xue et al. 2007), thermodynamic effects such as bright band effects (Jung et al. 2008b) and attenuation (Xue et al. 2009).

It is possible to do simultaneous state estimation and attenuation correction using EnKF, as first proposed by Xue et al. (2009).

The effectiveness of the approach in Xue et al. (2009) is demonstrated using a set of observing system simulation experiments (OSSEs), in which observations collected from a model-simulated supercell thunderstorm through a radar are assimilated.
The forward observation operator with attenuation

The equation for the reflectivity calculation in the observation operator

\[ Z'(r) = 10 \log_{10} \left( \frac{Z_e}{1 \text{mm}^6 \text{m}^{-3}} \right) \int_0^r k(s) \, ds + \text{a random error} \]  

(1)

\[ Z'(r) \quad \text{reflectivity in dBZ after attenuation} \]

\[ Z_e \quad \text{equivalent radar reflectivity factor} \]

\[ k \quad \text{the attenuation coefficient} \]

To be consistent with Lin scheme used in prediction model, an exponential form DSDs is used

\[ N(D) = N_0 \exp(-LD) \]  

(2)

\[ N_0 \quad \text{is the intercept parameter and } \Lambda \text{ is the slope parameter} \]
The forward observation operator with attenuation

The hydrometeor content and radar variables are represented by weighted integrals over the DSDs as follows

\[ W = \frac{1}{6} D^3 N(D) dD \]  \hspace{1cm} (3)

\[ Z_e = \frac{4}{5 |K_W|^2} b(D) N(D) dD \]  \hspace{1cm} (4)

\[ k = 4.343 e(D) N(D) dD \]  \hspace{1cm} (5)

\[ W \] the hydrometeor mass content, in mass per unit volume of air

The parameterized relations between model predicted \( W \) with \( Z_e \) and \( k \) can be derived using (2) (3) (4) & (5):

\[ Z_e = \alpha_Z W^{\beta_z} \] \hspace{1cm} \& \hspace{1cm} \[ k = \alpha_k W^{\beta_k} \]

Applied the procedure to rainwater, dry snow and hail, wet snow and hail
The analytical observation error model (AEM)

Attenuated radar data inherently leads to spatially non-uniform observation errors. Larger observation errors will be assigned when observed reflectivity is smaller, which possibly indicates attenuation, while smaller observation errors will be used when observed reflectivity is larger.

\[
\text{if } Z_e < Z_{e_{-}\text{min}} \quad \sigma_{obs} = C \\
\text{else} \quad \sigma_{obs} = \sigma_{set} \times \max(\log\left(\frac{U}{Z_e}\right), 1.0)
\]

- \(Z_e\): the modified observation error variance
- \(Z_{e_{-}\text{min}}\): the original preset observation error variance
- \(C\): 8.0 (relation 1, 2)
- \(U\): 16.0 (relation 3)
- \(U\): 160.0 (relation 1)
- \(U\): 220.0 (relation 2, 3)
Test with simulated CASA (4 radars) observations

1500m in dx, dy
40 members
12 cycles (5 minutes interval)
Assimilate Z & Vr

Forecast: ARPS model
Analysis: EnSRF

ATC (Forward observation operator w/ attenuation)

OBSE (Forward observation operator w/ attenuation + AEM)
Test with simulated CASA (4 radars) observations

RMS errors of analysis

Gray: ATC (Forward observation operator w/ attenuation)
Red: OBSE (Forward observation operator w/ attenuation + AEM)
Blue: OBSEONLY (Forward observation operator w/o attenuation + AEM)

RMS errors are calculated inside radar coverage
Test with real CASA observations

The Tornado Outbreak of May 24, 2011

Tornado C1: showed up at 2206 UTC, last 55 minutes
Tornado D1: showed up at 2226 UTC, last 49 minutes
GOES-13 Visible Images
The experiment design (domain and resolution)

Initialized from NAM 12 km analyses at 1800 UTC, 24 May 2011

\[
\begin{align*}
dx_1 &= 1500 \text{m} & dx_2 &= 500 \text{m} \\
dy_1 &= 1500 \text{m} & dy_2 &= 500 \text{m} \\
nx_1 &= 363 & nx_2 &= 363 \\
ny_1 &= 363 & ny_2 &= 435 \\
Ctrl_{lat}1 &= 34.500 & Ctrl_{lat}2 &= 34.707 \\
Ctrl_{lon}1 &= -97.807 & Ctrl_{lon}2 &= -97.803
\end{align*}
\]

To generate initial ensemble members on outer domain
2 m/s Gaussian random perturbation on \(u, v\)
1 K perturbations on \(\theta\)
The experiment design (timeline)

1800UTC: Spin up Radar (88D) and Mesonet data assimilation for 1 hour, 15 min interval.

1900UTC: Okla. Mesonet data.

2000UTC: Radar (88D) and Mesonet data assimilation for 1 hour, 15 min interval.

2100UTC: Ensemble forecast to provide ensemble PBLs.

2200UTC: Radar data assimilation, CASA and 88D, 5 min interval.

2300UTC: Forecast.

Tornado C1 (2206 UTC)

Tornado D1 (2226 UTC)
The list of experiments on inner domain grids

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Observation Assimilated</th>
<th>Attenuation Correction in EnKF</th>
<th>Observation Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNTL</td>
<td>Ref. and Vr of WSR-88D</td>
<td>N</td>
<td>3 m/s for Vr, 5dB for Ref 88D and CASA</td>
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<tr>
<td></td>
<td>Pre-corrected Ref. and Vr of CASA</td>
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</tr>
<tr>
<td>ATTC</td>
<td>Ref. and Vr of WSR-88D</td>
<td>Y</td>
<td>3 m/s for Vr, 5dB for Ref 88D; AEM applied to CASA</td>
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<tr>
<td></td>
<td>Un-corrected Ref. and Vr of CASA</td>
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</table>
The radar observations

CASA observed reflectivity at 2135UTC on 2 degree elv.

Blue color indicates the 0 reflectivity
The analysis results on inner domain grids

Assimilated CASA Uncorrected Reflectivity

2 km 2135 UTC
The deterministic forecast (10 minutes)
The deterministic forecast (20 minutes)
The deterministic forecast (30 minutes)
The deterministic forecast (40 minutes)
The deterministic forecast (50 minutes)
The deterministic forecast (60 minutes)
The ensemble forecast (40 members)

The frequency count of low-level vortices above 0.012 1/s

CTRL

ATTC

(a)

(b)
The frequency count of low-level vortices above 0.008 1/s
Summary and discussion

• In this study, an approach of simultaneous state estimation and attenuation correction for convective storm system within ensemble Kalman filter (EnKF) data assimilation (DA) system has been improved and tested in the Observing System Simulation Experiments (OSSEs) and applied to real case for the first time.

• In OSSEs, our attenuation correction procedure is proved to be effective by applying forward observation operator considered attenuation and an empirical observation error model (AEM) together. Such procedure is also proved to be robustness through imperfect model experiments.

• Assimilating un-corrected CASA data directly using EnKF with built-in attenuation correction procedure shows significant improvement compared to the one using pre-corrected CASA data.

• Our method uses attenuated observations directly and is mainly based on model state variable estimation in EnKF. The pre-correction however requires Dual-Polarization radar measurements, or needs to estimate PIA independently to avoid numerically unstable problem.
Thanks!

Questions And Comments?
**Verify against Oklahoma Mesonet observation**

### Temperature (C)

<table>
<thead>
<tr>
<th></th>
<th>Minco</th>
<th>Norman</th>
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<tbody>
<tr>
<td>OK Mesonet (OBS)</td>
<td>22.48</td>
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<tr>
<td>CNTL</td>
<td>24.40</td>
<td>26.8</td>
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<td>23.24</td>
<td>26.56</td>
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### RH (%)

<table>
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<th>Norman</th>
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<tbody>
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<td>76.42</td>
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<td>CNTL</td>
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<td>ATTC</td>
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<td>73.20</td>
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