Impact of Geostationary Satellite Borne Precipitation Radar on NWP: An OSSE with an EnKF for a Typhoon Case

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What’s next for satellite-borne radar?

GPR (Geostationary satellite borne Precipitation Radar) is one of the potential missions as a successor of GPM/DPR.

GOAL: To investigate the impact of GPR on typhoon forecast
Today’s contents

1. What kind of observation can GPR get?
2. Impact of GPR on NWP
Simulating precipitation radar observations from GPR

What kind of observation can GPR get?

Advantage
- Quasi-continuous precipitation observation (c.f. TRMM overpasses 500km-500km box 1-2 times/day)

Disadvantage
- Relatively coarse horizontal resolution (i.e. large sampling volume) (c.f. 5km in GPM/DPR)
- Tilted sampling volume at the off-nadir
  \[ \rightarrow \text{severe ground clutter} \]
Simulation of GPR observation

Radar-received power from precipitation ($P_r$):

$$P_r = \frac{P_t \lambda^2}{(4\pi)^3} \int_{r_0-c\tau/4}^{r_0+c\tau/4} \int_{\theta_0+\pi}^{\theta_0+\pi/2} \int_{\phi_0-\pi/2}^{\phi_0+\pi/2} f^4(\theta, \phi) \bar{\sigma}_b(r, \theta, \phi) r^{-2} \cos \theta \ d\phi \ d\theta \ dr$$

$\theta, \phi$: Scan angle

$r$: Range

$f^4(\theta, \phi)$: Beam pattern (2-way). Gaussian pattern approximated by 5th order polynomial is used

$\bar{\sigma}_b(r, \theta, \phi)$: total backscattering calculated with Joint-Simulator (Hashino et al., 2013; Masunaga & Kummerow, 2005). Single particle backscattering is calculated by assuming the Mie-approximation.
Simulation of GPR observation

Radar-received power from the surface ($P_s$)

\[ P_s = \frac{P_t \lambda^2}{(4\pi)^3} \int \int_A \frac{f^4(\theta, \phi)\sigma_0}{r^4} dA \]

Normalized radar cross section (NRCS) for sea surface
(Wentz et al., 1984)

\[ \sigma_0 = b_0(U_{10})^{b_1} \]

$P_s \sim$ surface wind speed and incident angle
Simulation of GPR observation

Model Simulation

Qr, Qc, Qs, Qi, Qg

Joint Simulator

Calculate surface echo

\( \bar{\sigma}_b, k_{ext} \)

Integrate \( \bar{\sigma}_b, k_{ext} \) and \( \sigma_0 \) following beam pattern

Pr, Ps

Model space value

Observation space value
Simulation of GPR observation: A real case

Simulation of GPR observation: A real case

Simulation of GPR observation (revised)

Radar-received power from precipitation \( (P_r) \):

\[
P_r = \frac{P_t \lambda^2}{(4\pi)^3} \int_{r_0-c\tau/4}^{r_0+c\tau/4} \int_{\theta_0+\pi}^{\theta_0+\pi/2} \int_{\phi_0-\pi}^{\phi_0+\pi/2} f^4(\theta, \phi) \bar{\sigma}_b(r, \theta, \phi) A_P(r, \theta, \phi) r^{-2} \cos\theta \, d\phi \, d\theta \, dr
\]

\( \theta, \phi \): Scan angle

\( r \): Range

\( f^4(\theta, \phi) \): Beam pattern (2-way). Uniform-distribution is assumed

\( \bar{\sigma}_b(r, \theta, \phi) \): total backscattering calculated with Joint-Simulator (JS; Masunaga & Kummerrow, 2005). Single particle backscattering is calculated by assuming the Mie-approximation.

\( A_P(r, \theta, \phi) \): Attenuation coefficient.

\[
A_P(r, \theta, \phi) = \exp\left[-2 \int_0^r \bar{k}_{ext}(r', \theta, \phi) \, dr'\right], \text{ where } \bar{k}_{ext} \text{ is extinction coefficient calculated by JS}
\]
Simulation of GPR observation: A real case w/ sidelobe clutter & attenuation


![Nature run](a) ![GPR obs (20km)](b) ![GPR obs (20km) (oversampling)](c) ![GPR obs (5km)](d)

- **Main lobe clutter contaminated area**
- **Sidelobe clutter contaminated area**
Simulation of GPR observation: A real case w/ sidelobe clutter & attenuation

Threshold=20 [dBZ]

(a) bw20–bs20

(b) bw20–bs05

(c) bw05–bs05

Threshold=50 [dBZ]

(d) Threat Score

(e) Threat Score

(f) Threat Score

Legend:
- w/o attenuation & w/o clutter
- w/o attenuation & w/ clutter
- w/ attenuation & w/o clutter
- w/ attenuation & w/ clutter
Assimilation of Radar reflectivity for Tropical Cyclone with an EnKF

Preparatory experiments for GPR assimilation
Difficulty in reflectivity assimilation

- Assimilation of radar reflectivity fails to produce deepening of tropical cyclone (Dong & Xue, 2013)

![Graph showing MSLP over time with different experiments and the best track.](image-url)
Is it possible to simulate TC only with Z...?
Conventional view of TC intensification

I. Inflowing air acquires heat
II. Convection in the inner-core region
III. Convergence in the lower boundary layer is accelerated
IV. Advepts angular momentum
V. Intensify primal circulation
VI. TC deepening through gradient adjustment

TC must be intensified by assimilating reflectivity

Schematic of height-radius cross-section of TC
Montgomery & Smith (2010)
Experimental Design

- **Experiment type**
  - Perfect model OSSE

- **Case**
  - Typhoon Soudelor (2015)

- **Observation**
  - Radar reflectivity at all the model grid point
  - Frequency: 1 [h]
  - Error: 5 [dBZ]

- **DA system**
  - SCALE-LETKF (Lien et al., 2017)
  - Joint-Simulator (Hashino et al., 2013) to calculate radar reflectivity
  - 50 members
  - Localization: H: 10km, V: 0.3lnp
  - Inflation: RTPP with $\alpha = 0.8$ (Zhang et al., 2004)
  - Thinning: 1/25 horizontally & 1/5 vertically
  - Clear reflectivity shift (G.-Y. Lien, personal communication)
    $$ y = \begin{cases} 
    y & (y \geq 20dBZ) \\
    15 & (y < 20dBZ) 
    \end{cases} $$
    (similar to Aksoy et al., 2009, but leave a 5-dBZ gap)
$Z @ 1000[m]$: temporal evolution

2015/7/29 0700 – 2015/7/30 0900
SLP: temporal revolution

2015/7/29 0700 – 2015/7/30 0900

SLP fields are contaminated by noise!
Where does the noise come from?

- \( \text{dBZ}_{\text{anal}} (>20) \)
- \( \text{dBZ}_{\text{gues}} (>20) \)
- \( |\partial P_s / \partial t| (=1 \text{ Pa s}^{-1}) \)

\( |\partial P_s / \partial t| \): metric of imbalances
(Lange and Craig, 2014; Bick et al., 2016)
Localization and Imbalance

Localization induces imbalance
(Lorenc, 2003; Greybush et al., 2011)

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Obs.</th>
<th>Localization</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoDA</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Loc-30km</td>
<td>Z</td>
<td>$\sigma_H = 30km$</td>
</tr>
<tr>
<td>Loc-50km</td>
<td>Z</td>
<td>$\sigma_H = 50km$</td>
</tr>
<tr>
<td>Loc-100km</td>
<td>Z</td>
<td>$\sigma_H = 100km$</td>
</tr>
</tbody>
</table>

Analysis
Forecast from the ensemble mean
Sensitivity to the localization scale

![Diagram showing sensitivity to the localization scale for Reflectivity (dBZ) and SLP (hPa). The images depict simulations for different localization scales: Nature, LOC-10km, LOC-50km, LOC-100km. The diagrams illustrate the impact of different scales on the representation of weather patterns.]
Localization in previous radar-DA

<table>
<thead>
<tr>
<th>Reference</th>
<th>Ensemble size</th>
<th>Analysis grid (km)</th>
<th>Localization cutoff (r, km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snyder and Zhang (2003)</td>
<td>50</td>
<td>2</td>
<td>H: 4; V: 4</td>
</tr>
<tr>
<td>Dowell et al. (2004)</td>
<td>50</td>
<td>2</td>
<td>H: 6; V: 6</td>
</tr>
<tr>
<td>Tong and Xue (2005)</td>
<td>100</td>
<td>2</td>
<td>H: 8; V: 8</td>
</tr>
<tr>
<td>Caya et al. (2005)</td>
<td>100</td>
<td>2</td>
<td>H: 7.3; V: 7.3</td>
</tr>
<tr>
<td>Aksoy et al. (2009)</td>
<td>50</td>
<td>2</td>
<td>H: 5; V: 4</td>
</tr>
<tr>
<td>Dowell and Wicker (2009)</td>
<td>50</td>
<td>1</td>
<td>H: 6; V: 6</td>
</tr>
<tr>
<td>Dowell et al. (2011)</td>
<td>50</td>
<td>1</td>
<td>H: 6; V: 6</td>
</tr>
<tr>
<td>Dong et al. (2011)</td>
<td>50</td>
<td>2</td>
<td>H: 6; V: 6</td>
</tr>
<tr>
<td>Dawson et al. (2012)</td>
<td>30</td>
<td>1</td>
<td>H: 12; V: 6</td>
</tr>
</tbody>
</table>

Sobash and Stensrud (2013)

**TC case**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Ensemble size</th>
<th>Analysis grid (km)</th>
<th>Localization cutoff (r, km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhang et al. (2009)</td>
<td>30</td>
<td>4.5</td>
<td>H: 135, 405 (SCE)</td>
</tr>
<tr>
<td>Aksoy et al. (2012)</td>
<td>30</td>
<td>3</td>
<td>H: 240</td>
</tr>
<tr>
<td>Dong and Xue (2013)</td>
<td>32</td>
<td>4</td>
<td>H: 12; V: 4</td>
</tr>
<tr>
<td>Zhang et al. (2016)</td>
<td>60</td>
<td>3</td>
<td>H: 30 (200) for hydro (others)</td>
</tr>
<tr>
<td>Honda et al. (2018)</td>
<td>50</td>
<td>3</td>
<td>H: 219</td>
</tr>
</tbody>
</table>
Another source of noise in SLP

- Sea Level Pressure (hPa)
- Variable localization (Kang et al., 2011)
Correlation b/w reflectivity and model prognostic variables

- $u$
- $v$
- $w$
- $q_v$
- $q_c$
- $q_r$
- $q_s$
- $q_i$
- $q_g$
- $p$
- $t$
Another issue: #Observation

More than 60% of the observations were rejected!
Difficulty in reflectivity assimilation with EnKF

- Increment is zero in case of XO, in which all the ensemble members do not have precipitation

\[
x^a = x^f + \frac{\text{cov}(x^f, \mathcal{H}(x^f))}{B + R} (y^o - \mathcal{H}(x^f))
\]

<table>
<thead>
<tr>
<th>observation</th>
<th>simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>☁️</td>
<td>☁️</td>
</tr>
<tr>
<td>☂️</td>
<td>☀️</td>
</tr>
<tr>
<td>☁️</td>
<td>FO</td>
</tr>
<tr>
<td>☀️</td>
<td>XO</td>
</tr>
<tr>
<td>☀️</td>
<td>FX</td>
</tr>
<tr>
<td>☀️</td>
<td>XX</td>
</tr>
</tbody>
</table>
A technique to avoid XO: Averaging

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Observation</th>
<th>Guess</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid w/ precipitation</td>
<td>FO XO</td>
<td></td>
</tr>
<tr>
<td>Grid w/o precipitation</td>
<td>FX XX</td>
<td></td>
</tr>
</tbody>
</table>

Spread is zero → observation in this grid cannot be assimilated

Spread is NOT zero
Experimental Design

- **Experiment type**
  - Perfect model OSSE

- **Case**
  - Typhoon Soudelor (2015)

- **Observation**
  - Radar reflectivity at all the model grid point
  - Frequency: 1 [h]
  - Error: 5 [dBZ]

- **DA system**
  - SCALE-LETKF (Lien et al., 2017)
  - Joint-Simulator (Hashino et al., 2013) to calculate radar reflectivity
  - 50 members
  - Localization: \(H: 100\text{km}, V: 0.2\text{km}\)
  - Inflation: RTPP with \(\alpha = 0.8\) (Zhang et al., 2004)
  - Clear reflectivity shift (GY Lien, personal communication)
    \[
    y = \begin{cases} 
    y \ (y \geq 20dBZ) \\
    15 \ (y < 20dBZ) 
    \end{cases}
    \]
    (similar to Aksoy et al., 2009, but leave a 5-dBZ gap)
Experimental Design (cont.)

NCEP/GFS

00 UTC 2015/7/20
00 UTC 2015/7/21
18 UTC 2015/7/28
00 UTC 2015/7/29
12 UTC 2015/8/1

Nature run (D1)
Nature run (D2)

PREPBUFR

[GFS → D1] IC

[PREPBUFR obs. /every 6hr]

[D1 → D2] IC /every 1hr

[D2] obs. /every 1hr

[Nature run → D2] obs. /every 1hr

[gfs→d1] BC /every 6hr

[gfs→d1] IC
Experimental Design (cont.)

- **Experiments**
  - NoDA
    - Free run
  - **w/o averaging**
    - Assimilate radar reflectivity
    - Thinning: 1/25 horizontally & 1/5 vertically
  - **w/ averaging**
    - Assimilate averaged radar reflectivity
      \[ y^o, Hx^b = 10 \ln(\sum Z^{o,b}) \]
    - Averaging scale: 5x5 horizontally
    - Thinning: 1/5 vertically
    - the number of obs is the same as **w/o averaging**
TC intensity is well analyzed and predicted compared to NoDA. W/ averaging is better than w/o averaging for MSLP. Track error grows quickly in the forecast.
TC intensity is well analyzed and predicted compared to NoDA. W/ averaging is better than w/o averaging for MSLP.

Track error grows quickly in the forecast.
Correlation b/w reflectivity and model prognostic variables

- Z vs. u (domain average)
- Z vs. p (domain average)
- Z vs. qv (domain average)
- Z vs. qs (domain average)
- Z vs. v (domain average)
- Z vs. tk (domain average)
- Z vs. qc (domain average)
- Z vs. qi (domain average)
- Z vs. w (domain average)
- Z vs. qr (domain average)
- Z vs. qg (domain average)
Increment in height-radius cross section

Intensified secondary circulation

→ Angular momentum advection inward (strengthen tangential wind)

→ Deepening of TC following gradient balance

\[
\frac{1}{\rho} \frac{\partial p}{\partial r} = \frac{v^2}{r} + f\nu
\]

Composites of azimuthally averaged radius–height cross sections at 10 different times (every hour from 1800 UTC 1 Aug to 0000 UTC 2 Aug).
TC intensity is well analyzed and predicted compared to NoDA.

w/ averaging is better than w/o averaging for MSLP.

Track error grows quickly in the forecast.
Averaging improves precipitation

Nature run w/ Averaging w/o Averaging

Q_r [g/kg]

#Obs (after QC)
59704 → 75807
@1
st cycle

12Z02AUG2015
(24
th cycle)
TC intensity is well analyzed and predicted compared to NoDA. W/ averaging is better than w/o averaging for MSLP. Track error grows quickly in the forecast.
Why does the forecast track error grow quickly?

TC track is largely controlled by steering flow and $\beta$-effect

- **NoDA (BDYENS)**
- **NoDA (BDYT)**

**Track error decreased**

- **Westerly bias due to BC**
  - Substituting BC results in better track forecast
  - Large track error is not because of reflectivity assimilation!
MSLP

TC intensity is well analyzed and predicted compared to NoDA.

Track Error

Track error grows quickly in the forecast.
GPR Assimilation with an EnKF

An Observing System Simulation Experiment for a Typhoon Case
Experimental Design

- **Observation**
  - GPR (20km resolution / 20km sampling span; hourly)
  - TC-vital (TC-center position & MSLP; hourly)
  - Conventional data (PREPBUFR; hourly)

- **DA system**
  - SCALE-LETKF (Lien et al., 2017)
  - Joint-Simulator (Hashino et al., 2013) with GPR simulator (Okazaki et al., 2019)
  - 50 members
  - Localization: H: 100km, V: 0.2km
  - Inflation: RTPP with $\alpha = 0.8$ (Zhang et al., 2004)
  - Thinning: 1/25 horizontally & 1/5 vertically
  - Clear reflectivity shift (G.-Y. Lien, personal communication)
    
    $$ y = \begin{cases} 
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    \end{cases} $$

    (similar to Aksoy et al., 2009, but leave a 5-dBZ gap)

---

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<tr>
<th>EXP</th>
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</tr>
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<tbody>
<tr>
<td>CNV+TCV</td>
<td>Conventional obs. TC-vital</td>
</tr>
<tr>
<td>GPR</td>
<td>Conventional obs. TC-vital GPR measured Z</td>
</tr>
<tr>
<td>GPR w/ clutter</td>
<td>Conventional obs. TC-vital GPR measured Z (above 5km)</td>
</tr>
</tbody>
</table>
GPR at 1st DA cycle (13Z1AUG)
GPR at 3rd DA cycle (15Z1AUG)

Nature Run

GPR

CNV+TCv

[dbZ]

Ensemble mean of the analysis
GPR at 6\textsuperscript{th} DA cycle (18Z1AUG)

Ensemble mean of the analysis
GPR at 9th DA cycle (21Z1AUG)

Nature Run

GPR

CNV+TCv

Ensemble mean of the analysis
GPR at 12th DA cycle (0Z1AUG)
Why GPR (w/ clutter) is better?

- Reflectivity observations are detrimental for lower atmosphere
Summary and Future work

- We evaluated the potential of GPR for a typhoon case
- We demonstrated that GPR has a potential to improve forecasts for typhoon intensity
- GPR assimilation may benefit from its relatively large sampling volume
- The impact of surface clutter should be small on TC case
  - Reflectivity has high correlations at high altitude
  - TC is a tall system
- Additional impact of GPR when assimilated together with Himawari-8
Thank you!

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What is the best operation for GPR?

- GPR can measure the area around TCs densely (i.e. over-sampling)
Remaining issues…

- Highly non-Gaussian error distribution
  - Additive noise (Dowell & Wicker, 2009)
  - Pseudo-RH (e.g. Caumont et al., 2010) did not solve the problem
- Non-Gaussianity combined with nonlinearity in $\mathcal{H}$ makes it difficult to assimilate radar reflectivity effectively with EnKF
  - Gaussian Transform (Lien et al., 2013; 2016; Kotsuki et al., 2017)
  - Local PF (Poterjoy, 2016)
  - Hybrid-DA (e.g. E4DVar, EnVar) may be a good option?