Validation of a 3D Radar Mosaic Using Stochastic Simulation

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Acknowledgements:

SESAR 3D: Hassan al-Sakka (formerly Météo France)

STEPS: Clive Pierce (formerly Met Office), Martina Friedrich (Met Office)

Contents

1. SESAR prototype 3D radar reflectivity mosaic
2. Validation method: radar measurement simulation
3. Examples of results

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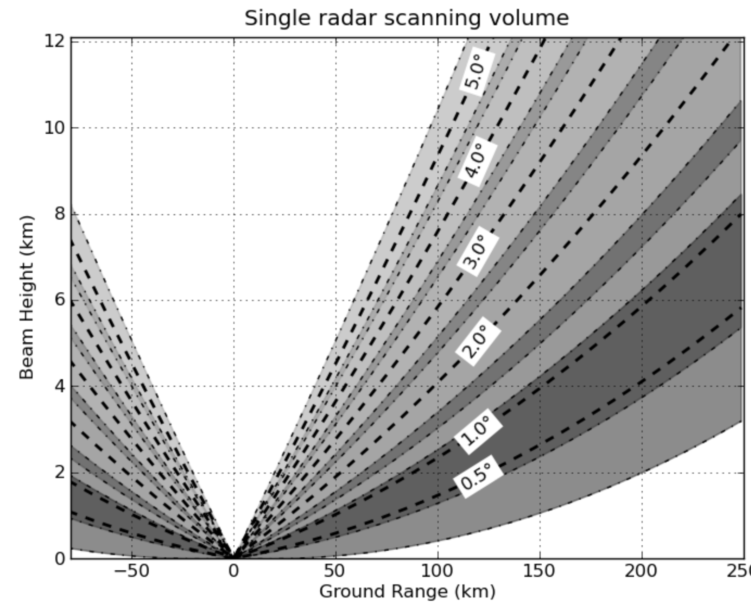
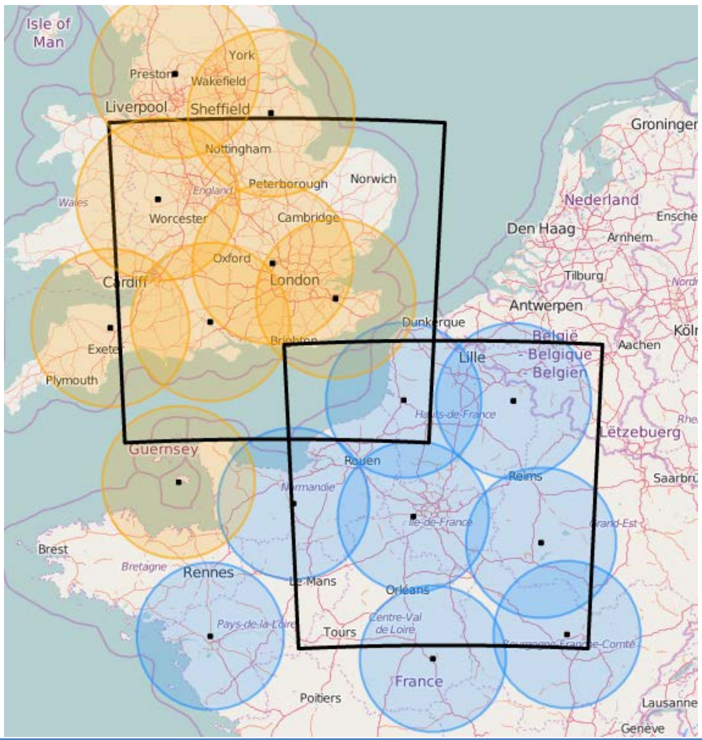
SESAR Prototype 3D Radar Reflectivity Mosaic

SESAR 3D Prototype

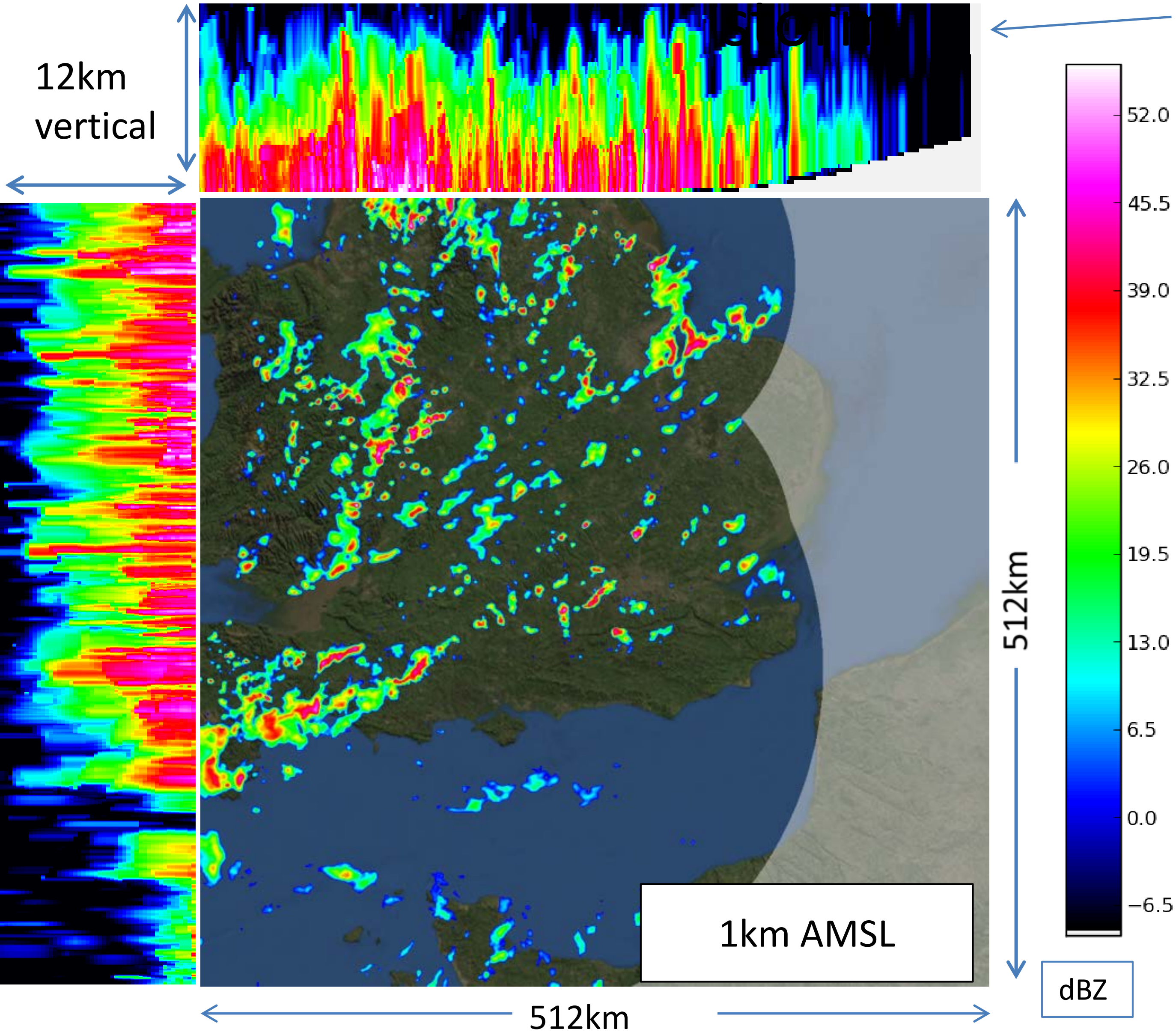
- Development project: 2013-2015
- Real time monitoring of severe convection in 3D
- 8 FR / 8 UK operational C-band radars
    - 5 PPI scans of Z / 5 minutes
    - 0.5° – 5.0° elevation
    - Δr = 600m, $\Delta\phi$ = 1.0°, ϕ_3 = 1.1°
- **3D gridded Z product**:
    - Barnes multi-pass retrieval
    - 1km horizontal / 500m vertical
    - 5 minute updates
    - 400km x 400km x 12km
- **2D column products**:
    - Vertically Integrated Liquid (VIL)
    - Echo top 18/45 dBZ
    - Max dBZ
- Ref: Scovell and al-Sakka, JTECH (2016)





100km (max 255km) coverage: orange: UK, blue: FR

3D dB[Z] retrieval for 2012-08-25 (12:10 UTC)



Top/Side Views: Maximum dB[Z] along lines of constant east / north

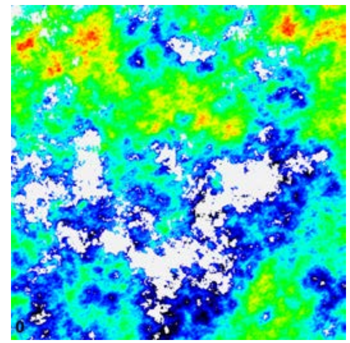
- 09:00 – 21:00 UTC
- Deep storm with widespread heavy showers and thunderstorms
- Storms reached 10 km in altitude

- True resolution limited to the scales resolvable by radar
- At long range, beam broadening limits true resolution

Overview of Validation Method

Radar Measurement Simulation

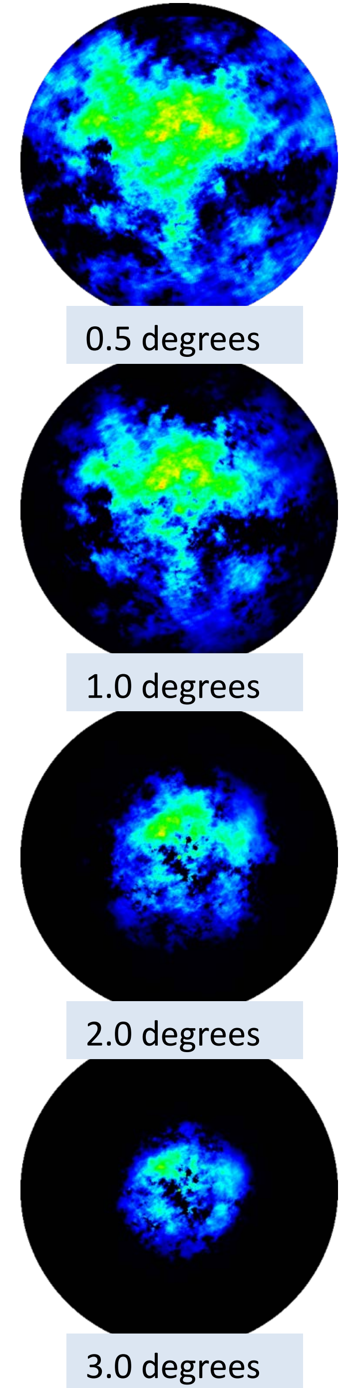
Synthetic 3D reference reflectivity at 2x resolution



Prior knowledge of 3D reflectivity statistics for a specific case

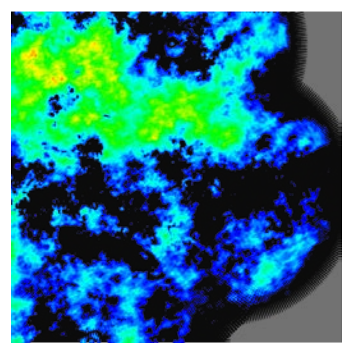
Simulate measurement + errors

Simulated Radar Network



Candidate 3D Retrieval Algorithm

Compare to synthetic



"Corrupted" 3D retrieval at 1x resolution

- Study of surface QPE errors
  - Sanchez-Diezma et. al (2000)
  - Llort et al. (2006)

Creation of 3D Reference Reflectivity

What to use for reference?

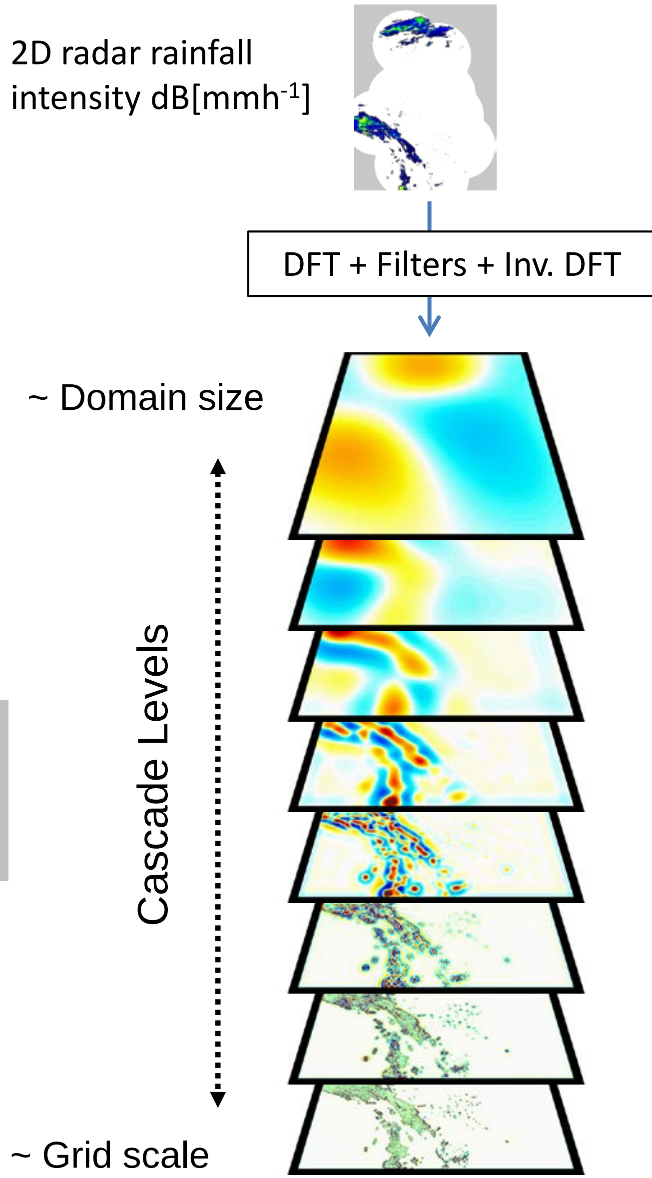
- Stochastic simulation
  - Allows direct control of spectral properties of data
  - Inexpensive to run compared with high-res NWP
  - Use features of Short Term Ensemble Prediction System (STEPS)
- Other authors: parameterized or fixed Vertical Profile of Reflectivity (VPR) modulated by horizontal 2D noise
  - Anagnostu and Krajewski (1997)
  - Llort et al. (2005)
  - Does not allow realistic fluctuations to the VPR shape needed for 3D validation
- Generate 2D synthetic dBZ fields, on 3D mosaic height levels, that are vertically correlated
  - Can get purely synthetic or a blend: radar analysis + synthetic

Scale Decomposition of 2D Rain Image

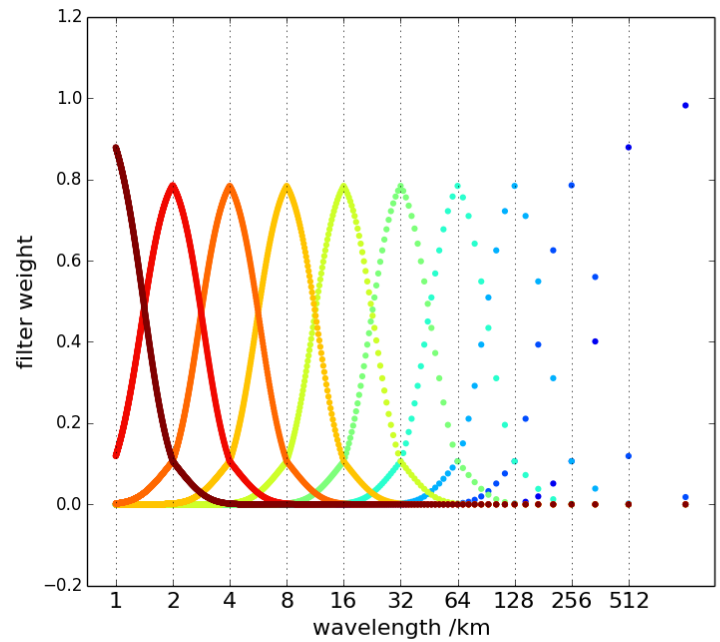
- STEPS models R as a **multiplicative cascade**
- Structures exist on a hierarchy of scales that combine multiplicatively
- Intensities of structures on a given scale treated as normally distributed

$$dBR_{i,j} = \sum_{n=0}^{N-1} X_{n,i,j}$$

for $i=1,..,L$, $j=1,..,L$, $L=2^{N-1}$

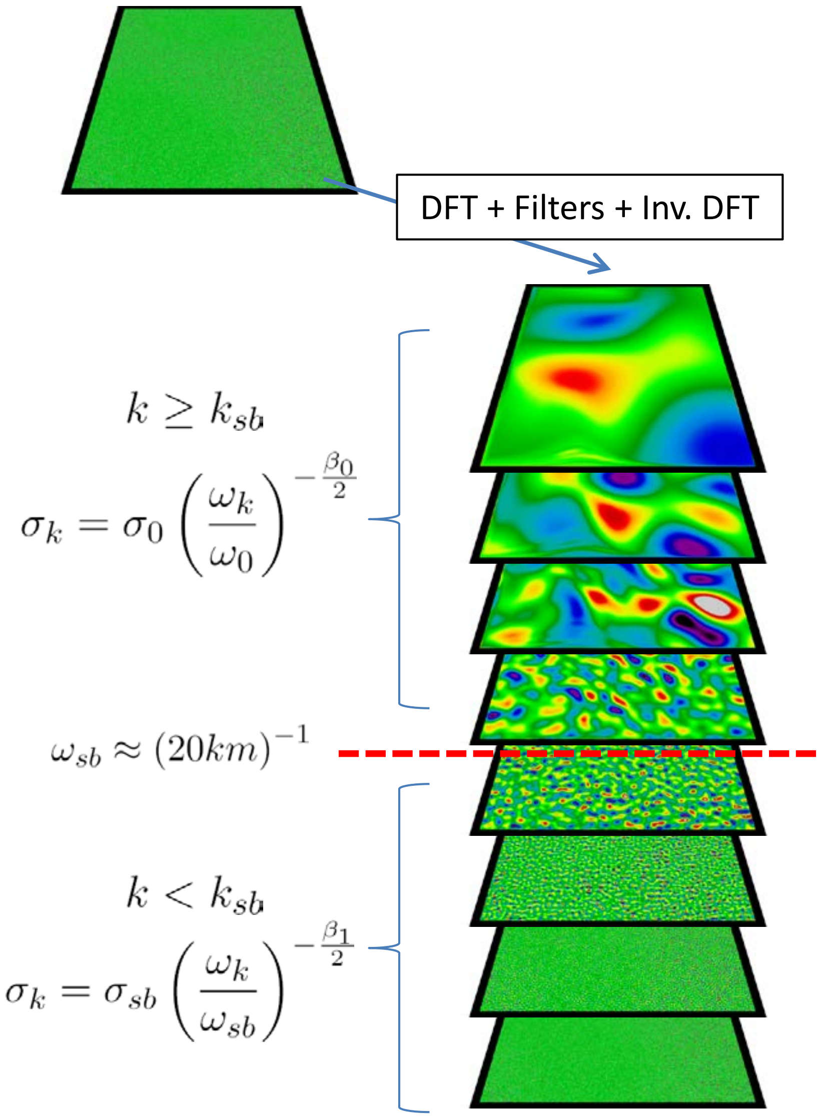


- Overlapping Gaussian filters
- Normalized so that sum = 1



Synthesis of 2D dBR / dBZ

Normally distributed white noise

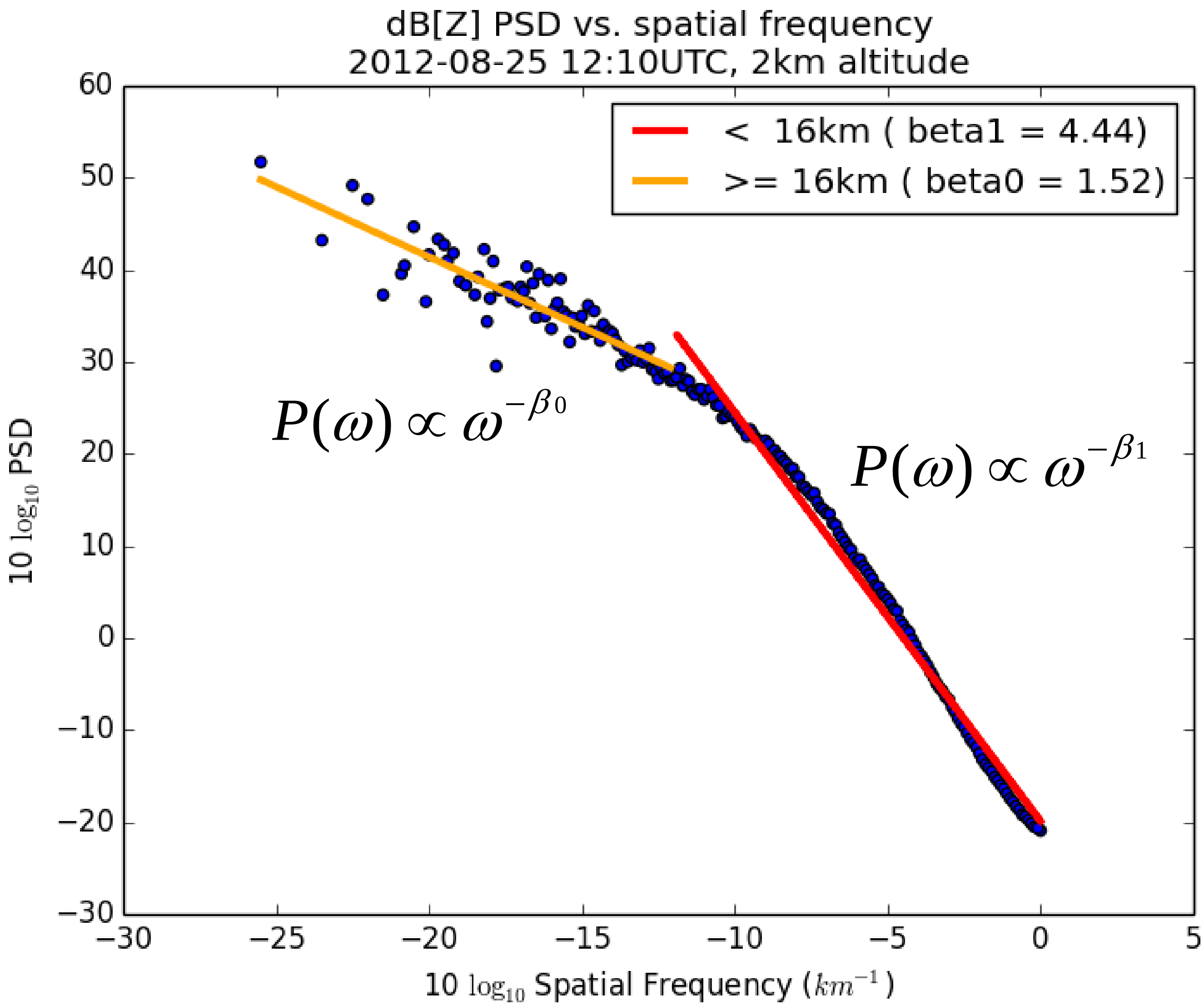


- Rain intensity is typically **scaling** over some range of scales:
  - $P(\omega) \propto \omega^{-\beta}$
- Usually see two distinct scaling regimes
  - β_0, β_1
- Scale break around 20km
- Determine β_0, β_1 to specify σ_k

- Assumption: dBZ can be modelled in the same way

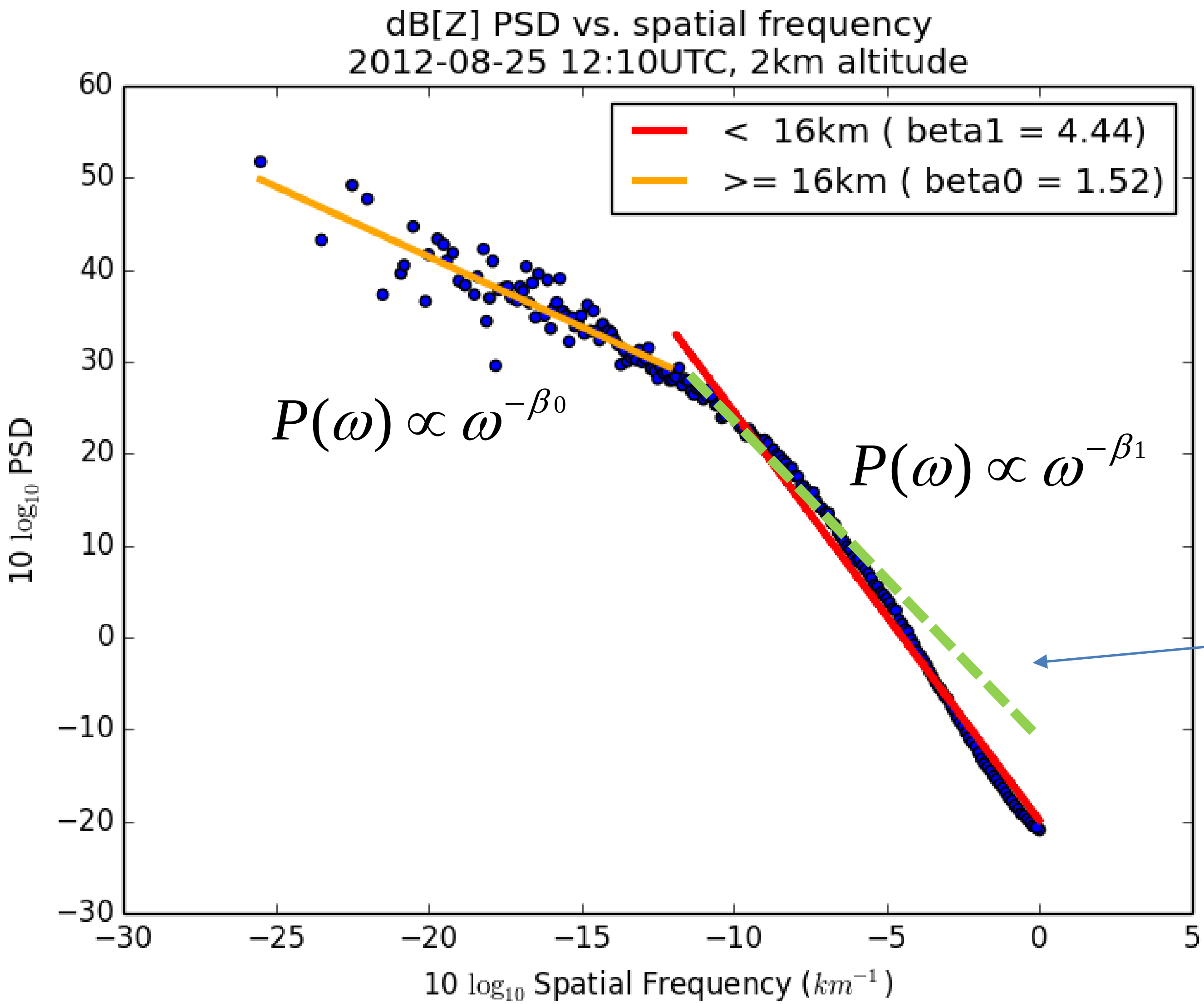
$$dB\left[Z_{ij}\right] = \sum_{k=0}^{N_k - 1} \sigma_k X_{k,ij}$$

Estimation of β_0, β_1 using the 25th August 2012 case



- Loss of power at short wave likely because of Barnes smoothing and radar sampling limitations.
- Various studies show β_1 tends to be less steep.
- E.g. Seed (2013) gives around 3-3.5 for an extreme storm (in Brisbane).

Estimation of β_0, β_1 using the 25th August 2012 case



Assumed β_1=3

Vertical Correlations on Scale Levels

- Vertical correlation between nearby levels varies with height
- STEPS scale decomposition cannot simply be extended into 3D

1. Scale decompose each height level L

- Transform to normal distribution
- Scale-decompose

2. Calculate $\mathbf{C}_k$ for each scale level k

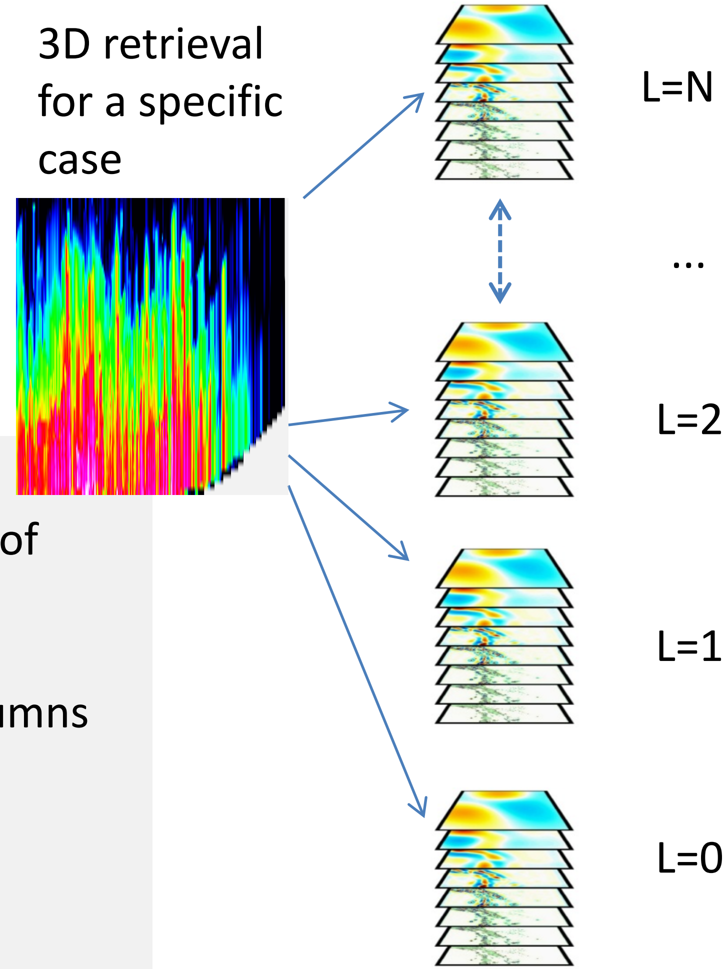
- Row / Col indexes are height levels: L_1, L_2
- Sample over all horizontal coordinates ij

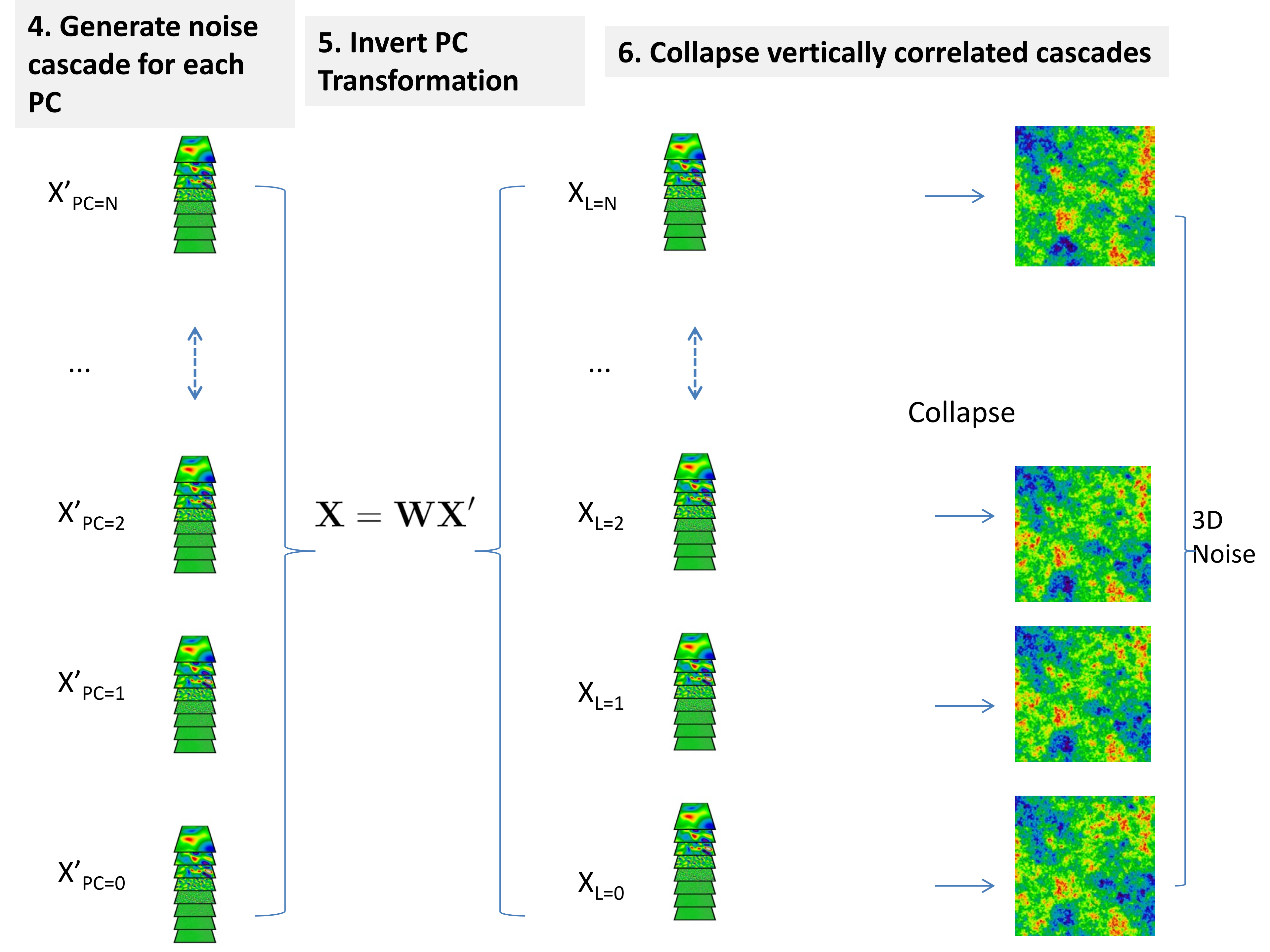
$$\mathbf{C}_{k,L_1,L_2} = \rho\left(Z_{k,L_1}, Z_{k,L_2}\right)$$

3. Principal Component Analysis

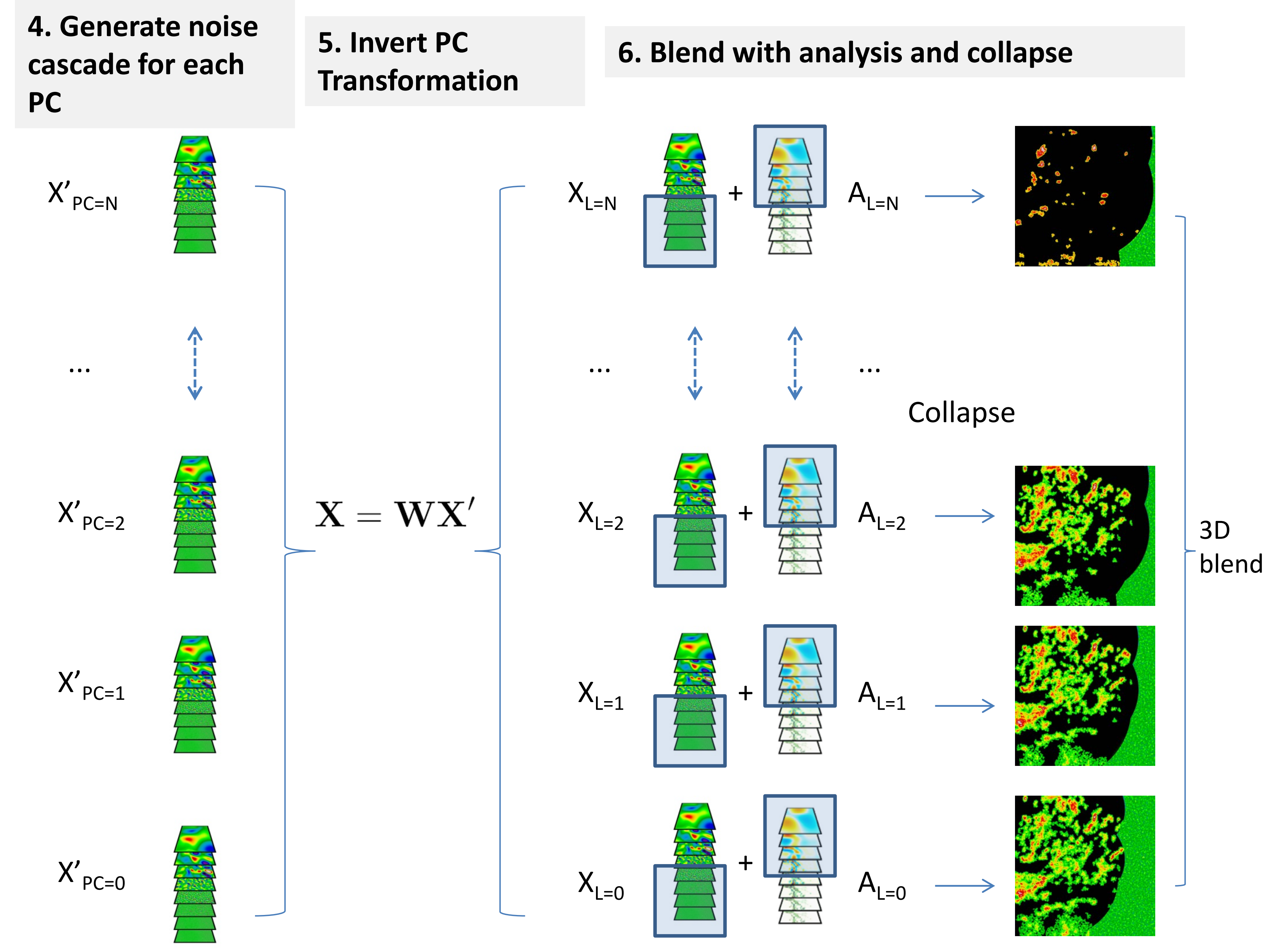
- Find independent modes of variability in a system of correlated variables
- Eigen-decomposition of $\mathbf{C}_k$
- Transformation $\mathbf{W}^T$ from vectors of 3D vertical columns of dBZ to vectors of principal components (PCs)
- Correlations between the PCs are zero

$$\mathbf{X}'_\mathbf{k} = \mathbf{W}_\mathbf{k}^\mathbf{T}\mathbf{X}_\mathbf{k} \qquad \mathbf{X}_\mathbf{k} = \mathbf{W}_\mathbf{k}\mathbf{X}'_\mathbf{k}$$

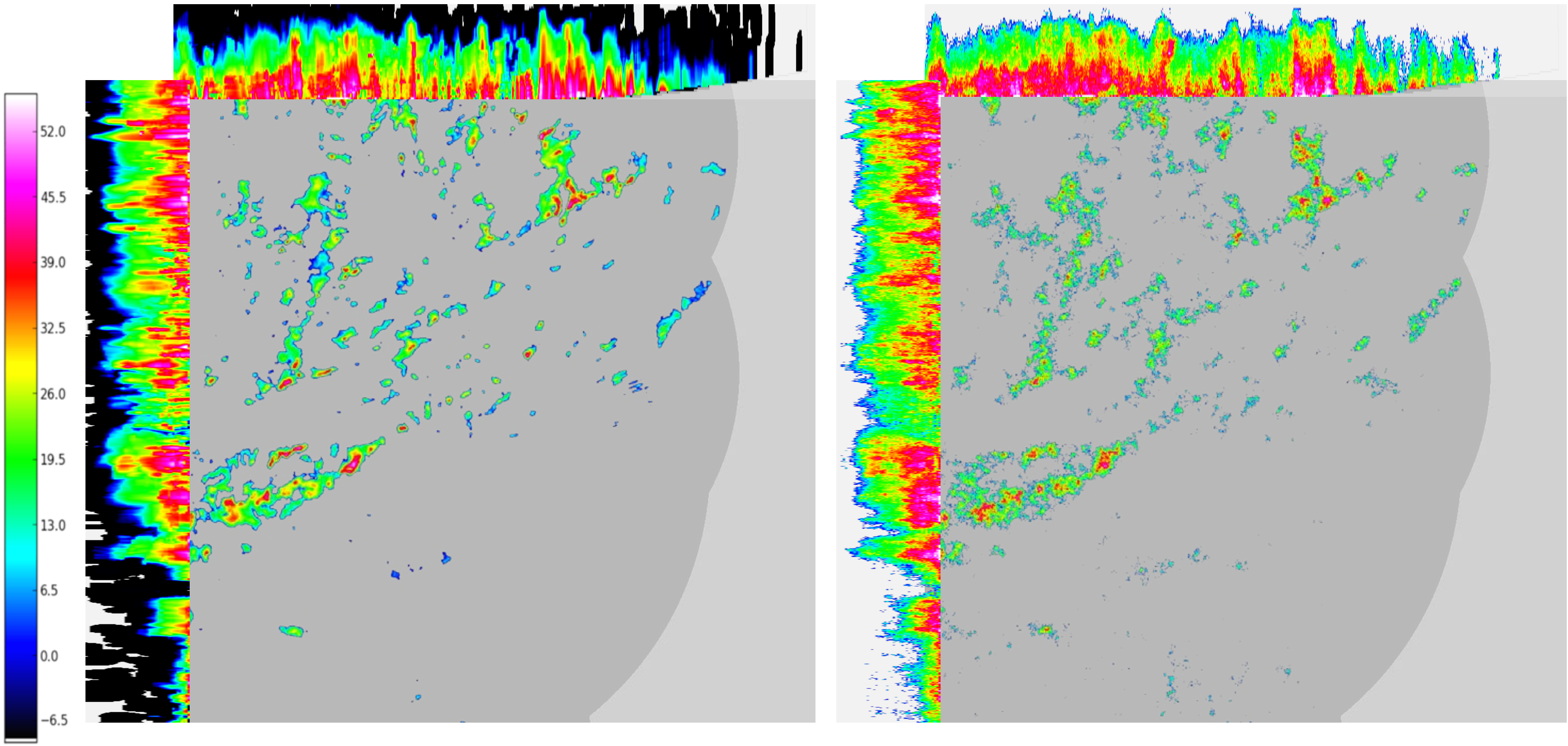




4. Generate noise cascade for each PC
5. Invert PC Transformation
6. Collapse vertically correlated cascades
$X'_{PC=N}$
...
$X'_{PC=2}$
$X'_{PC=1}$
$X'_{PC=0}$
$\mathbf{X} = \mathbf{W}\mathbf{X}'$
$X_{L=N}$
...
$X_{L=2}$
$X_{L=1}$
$X_{L=0}$
Collapse
3D Noise


4. Generate noise cascade for each PC
5. Invert PC Transformation
6. Blend with analysis and collapse
X'PC=N
...
X'PC=2
X'PC=1
X'PC=0
$\mathbf{X} = \mathbf{W}\mathbf{X}'$
XL=N
+
AL=N
...
...
Collapse
XL=2
AL=2
XL=1
AL=1
XL=0
AL=0
3D blend

Before and after blending



dB[Z]

- Assumed $\beta_1 = 3.0$
- Purely synthetic noise below scale break
- Removes signal where affected by beam smoothing and retrieval
- Finescale variability homogeneous throughout domain

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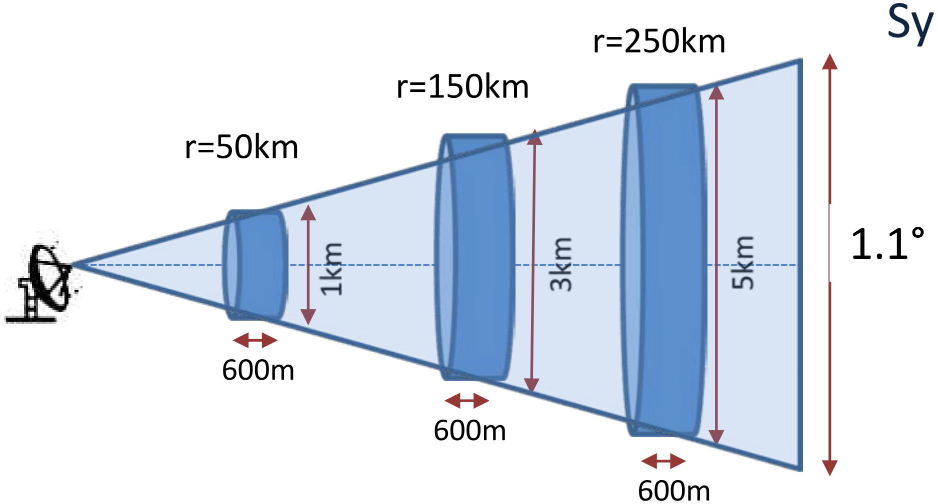
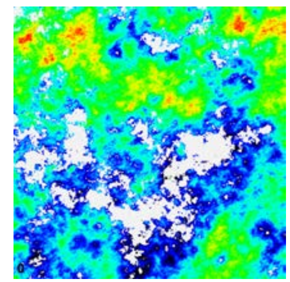
Simulation of radar network

Simulation of radar observations

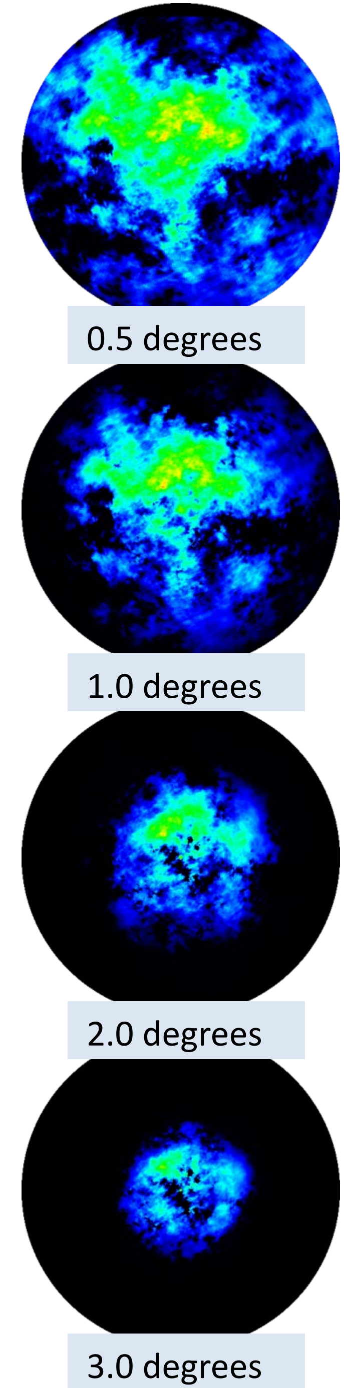


Synthetic 3D dB[Z] field



Simulate radar sampling

Simulated Radar Network



- Use approximate form of radar equation to simulate measurement:

$$Z_{SIM}(r_0, \phi_0, \theta_0) \propto \iiint_{V_s} Z_{SYN}(r, \phi, \theta)\, f^4(\phi', \theta')\, dV$$

- Numerically integrate over V_s
    - Z_{SYN} is computed from synthetic field at arbitrary points by tri-linear interpolation
    - f is approximated by: $f^2(\theta, \phi) = \exp\left[-4 \ln 2 \left(\frac{\phi^2}{\phi_3} + \frac{\theta^2}{\theta_3}\right)\right]$
-

•Z_{SIM} will reflect the finescale (sub-retrieval-grid) variability where radar can measure it

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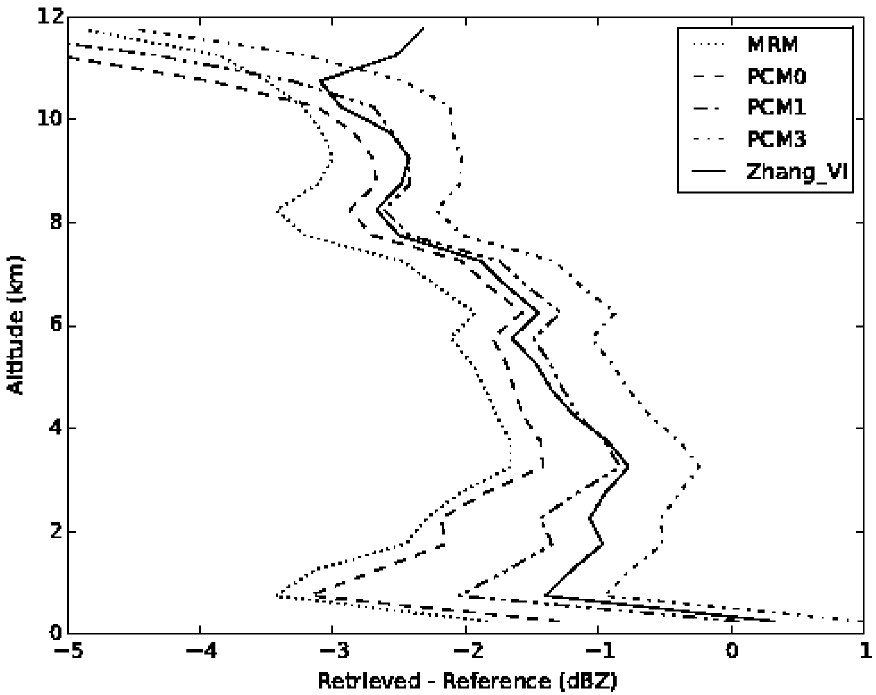
Examples of Validation Results

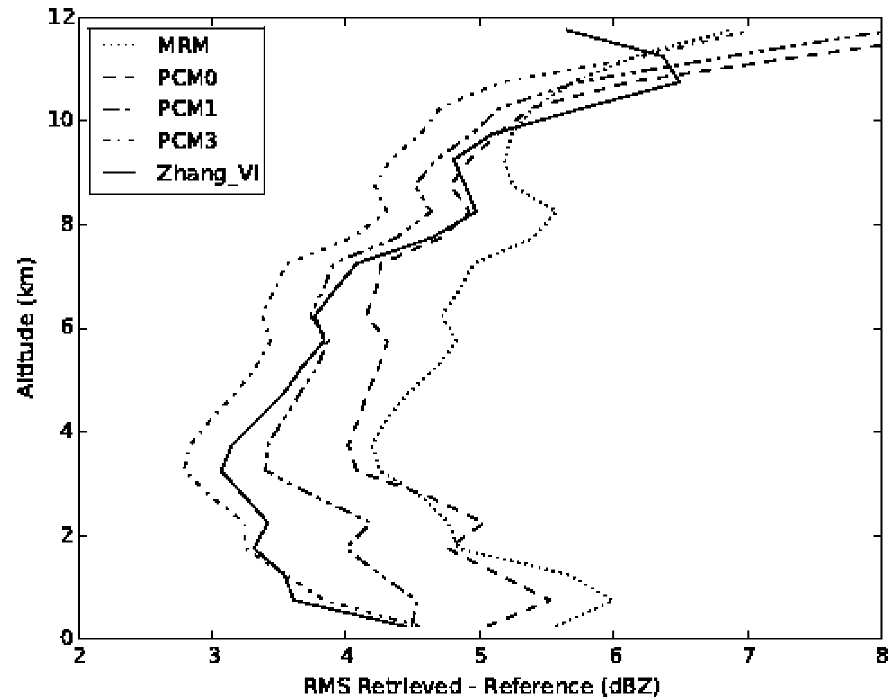
Inter-comparison of retrieval algorithms

•10 independent realisations of pure-synthetic data (based on 28-06-2012 case)
• Compare SESAR analysis (3 versions) to NOAA (Zhang *et al.* 2005; ZM) and Météo France method (Bousquet and Chong 1999; MRM)
• Caveat: in some cases observation biases will cancel retrieval biases, giving false confidence

Mean Error

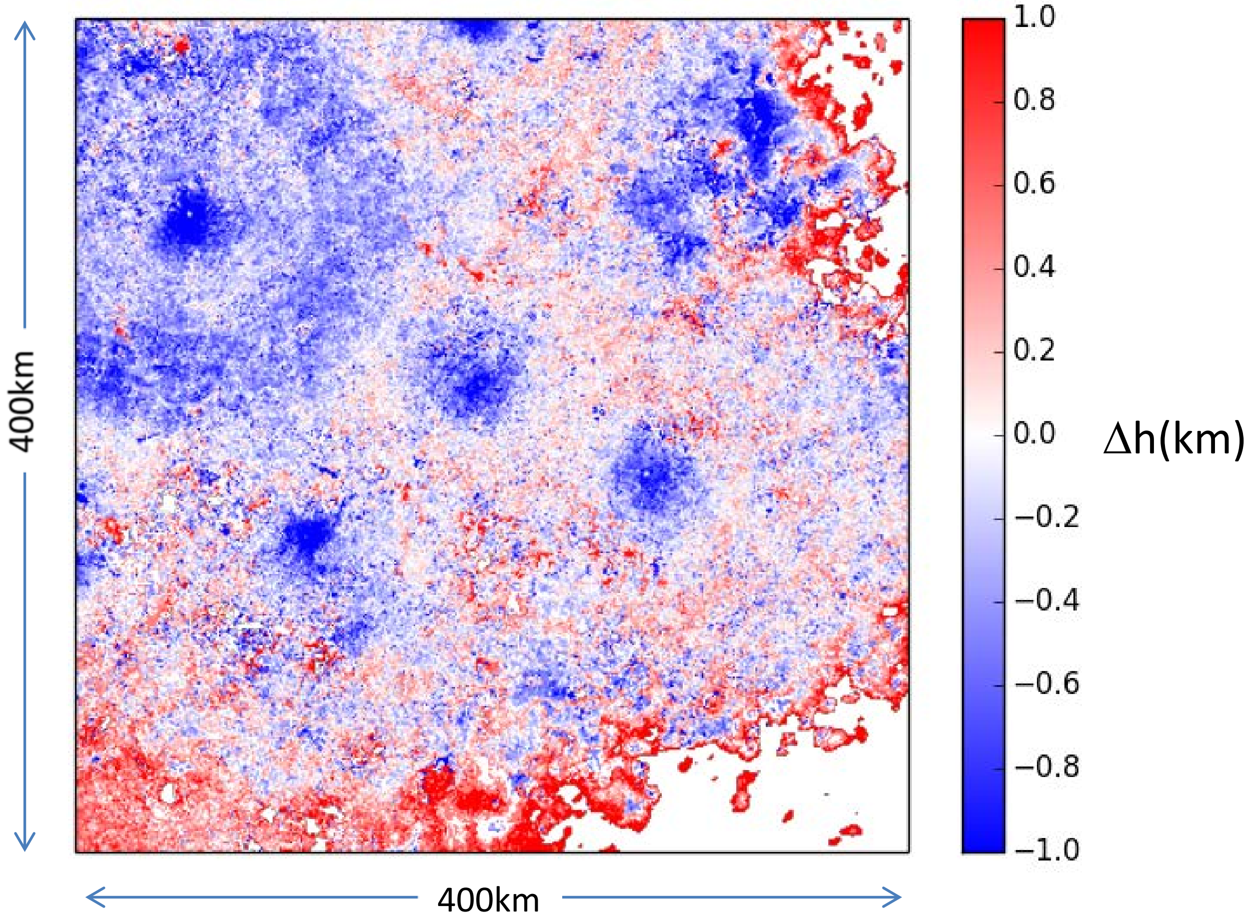


Root Mean Square Error



Scovell and al-Sakka, JTECH (2016)

Difference in 2D TOP18 product aggregated over 10 pure-synthetic fields



- Underestimation at short range (gaps above radar)
- Overestimation at long range (beam broadening)

ME ≈ -100m
RMSE ≈ 650m (r dep.)

Summary

- Method for creation of synthetic 3D mosaic
  - STEPS used to get 2D noise with a specified scaling exponent
  - Estimate of vertical covariance structure + PCA used to create height-correlated noise
  - [Temporal correlations using AR(2)]
- Used simulation evaluate and tune SESAR 3D mosaic
  - Comparison of different retrieval algorithms
  - Estimation of errors in retrieval
  - [Study of temporal sampling errors]
- Scope for this to be used in other contexts
  - Radar QPE (as others have done)
  - Radar network planning
- Other radar measurement errors could be introduced

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Questions?

Temporal Correlation using AR(2)

1. Compute motion vectors

- Use STEPS Optical Flow algorithm on lag-1 and lag-2 analyses
- OR supply an arbitrary flow field, e.g. for pure synthetic case

2. Advect previous noise cascades to current time t

- Apply motion vectors

3. Determine AR(2) model parameters on each scale k

- Use auto-correlation $p_k(t_0,t_1)$ and $p_k(t_0,t_2)$
- OR assume an exponential decay - half-life dependent on scale

AR(2) model parameters

$$Y_k\left(t\right) = \phi_{k,0}\left(t\right)\epsilon_k\left(t\right) + \phi_{k,1}\left(t\right)Y_k\left(t-\Delta t\right) + \phi_{k,2}\left(t\right)Y_k\left(t-2\Delta t\right)$$

Innovation (Lag-0 noise)

Advected Lag 1 Noise

Advected Lag 2 Noise

Temporal sampling errors

- Storm motion can result in poor 3D interpolation because storm features have moved from one scan to the next.
- This is particularly a problem when the cycle time is > 5 minutes and when there is strong advection.
- Time-synchronization can be achieved by applying motion vectors to PPI data, before gridding