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A concentration fluctuation model for virtual testing of detection systems

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Definition of Concentration Fluctuation

"The variation of concentration in space and time from an averaged distribution"

Why Model Concentration Fluctuation (1)

- Growing need to evaluate sensor network functionality and performance
- Development and testing of complex processing algorithms entirely using field data can be expensive and impractical
- Processing algorithms will often be developed in parallel with hardware

Why Model Concentration Fluctuation (2)

- Therefore a need for:
  - Realistic simulated challenge concentration fields
  - Realistic simulated background fields
- Problem Definition
  - **To develop a model which will enable us to simulate the behaviour of detectors within a real plume**

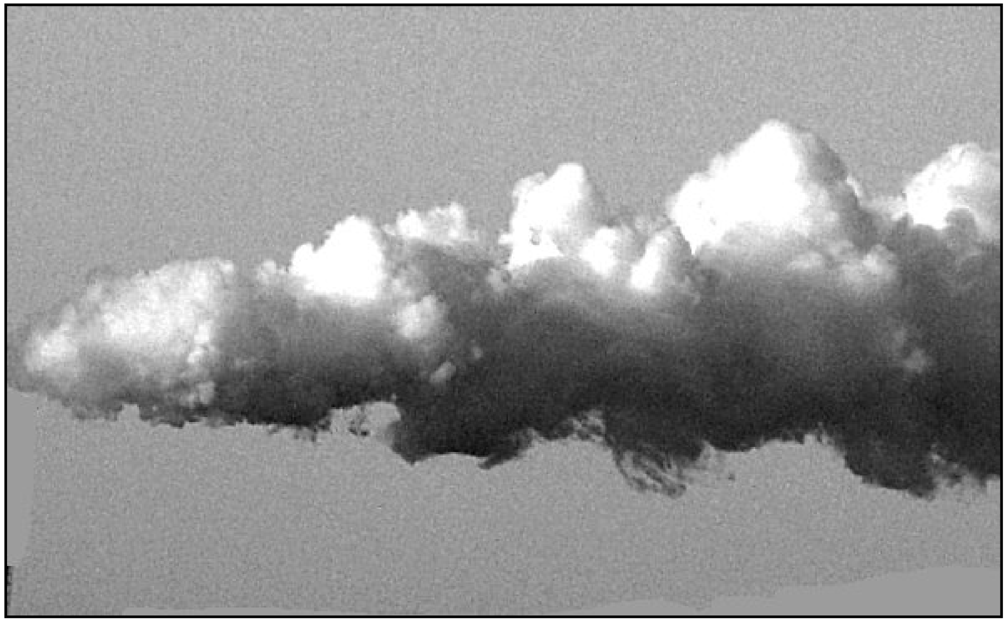
Existing Dispersion Model Approaches

- Gaussian puff models e.g. SCIPUFF, UDM
  - Produce ensemble predictions of concentration, with estimates of variance
- Single Particle models – e.g. NAME, FLEXPART
  - Produce ensemble mean predictions of concentration
- CFD
  - Dynamic CVD provides a detailed model but is computationally expensive
- Other technologies (e.g. LES, two particle models)
  - Could provide a detailed model, but are computationally expensive

Ensemble Models

- An ensemble is an average of all possible model runs
- BUT an ensemble looks very different to a real cloud AND real background data is very different from a flat mean value
- If we train and design our system against ensemble simulations we cannot expect it to behave in the same manner in a to real plume.

Real plume vs. ensemble plume



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Technical Approach

Fluctuation Characteristics (1)

- Concentration fluctuates around an ensemble mean value
- Fluctuations can be approximated by a **clipped** normal distribution
  - In some cases concentration can fall to zero
- Fluctuations show a degree of **temporal** correlation –
  - i.e. the concentration at time T + dT is related to concentration at time T

Fluctuation Characteristics (2)

- Fluctuations show a degree of **spatial** correlation
  - i.e. the concentration at a given location is correlated with the correlation at surrounding locations
- Spatial correlations have limited range
  - depends on fluctuation **length scale**
- Correlation down-wind is different to correlation cross-wind
  - Crosswind correlations have short range
  - Downwind correlations have longer range and a time delay

Possible approaches (1)

- Meander model and gaussian puff model (Gifford, 1959)
  - Produces large scale fluctuations but not small scale
- Markov chain (random walk) local concentration fluctuations
  - Models small scale fluctuations but without spatial
- Spatial correlation forcing. (i.e. adding correlation to independent fluctuation models)
  - Becomes an n-squared problem hence scales VERY badly on large scenarios

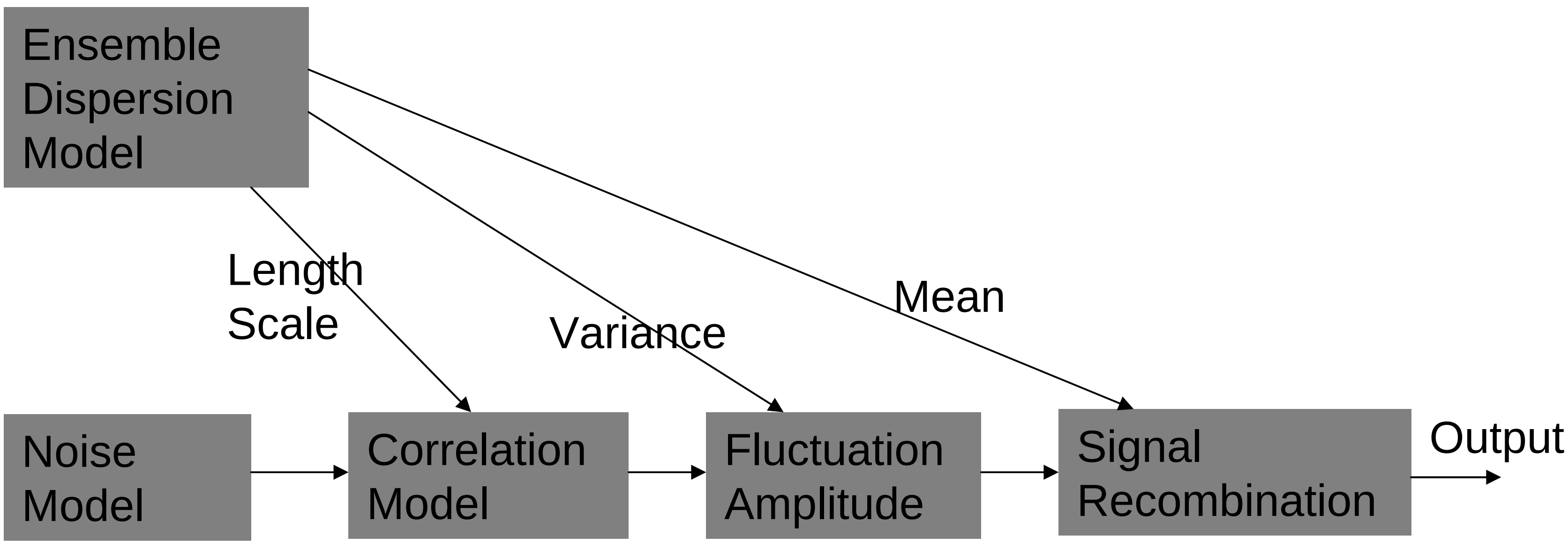
Possible approaches (2)

- Computational Fluid Dynamics
  - – Dynamic CVD could provide answers but very high computation cost
- Other technologies (e.g. LES, two particle models)
  - – Immature and un-validated for this domain of use
  - – Computationally expensive

Chosen approach – the Fluctuation Model

- Use a validated dispersion model to provide ensemble predictions
  - Concentration mean
  - Concentration variance
  - Fluctuation length scale
- Simulate a noise field separately
  - Using variance and fluctuation length scale from dispersion model
- Recombine with ensemble mean afterwards

Concentration Fluctuation Model - Software Architecture



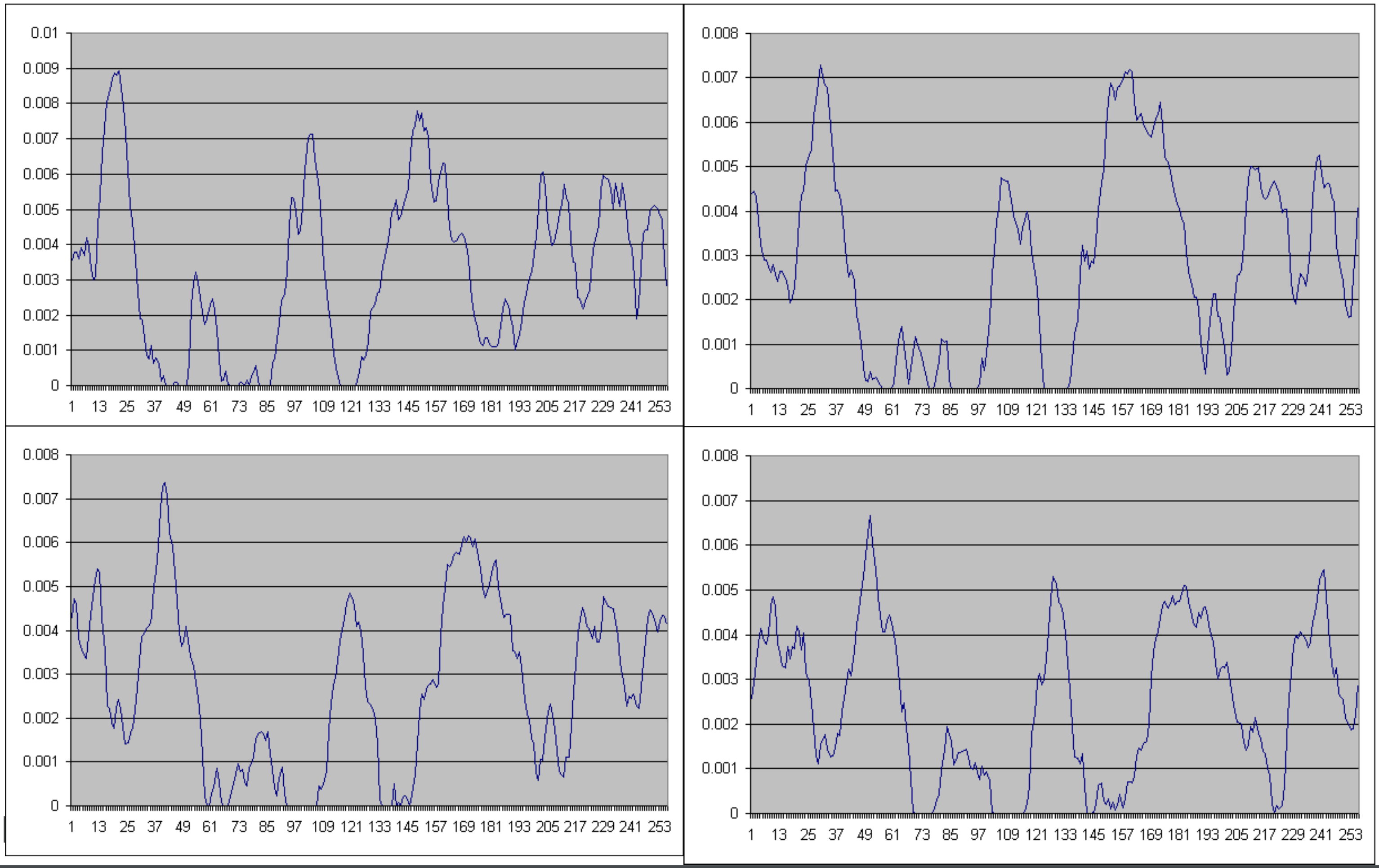
Model description (1) Noise Model

- Uses Hidden Markov Model (HMM) paradigm
- Underlying white noise field distributed over space
- Moves downwind with time
- Modified (mutated) with time
  - Via stochastic cell-swapping
  - Via individual random walk at pixel lebel

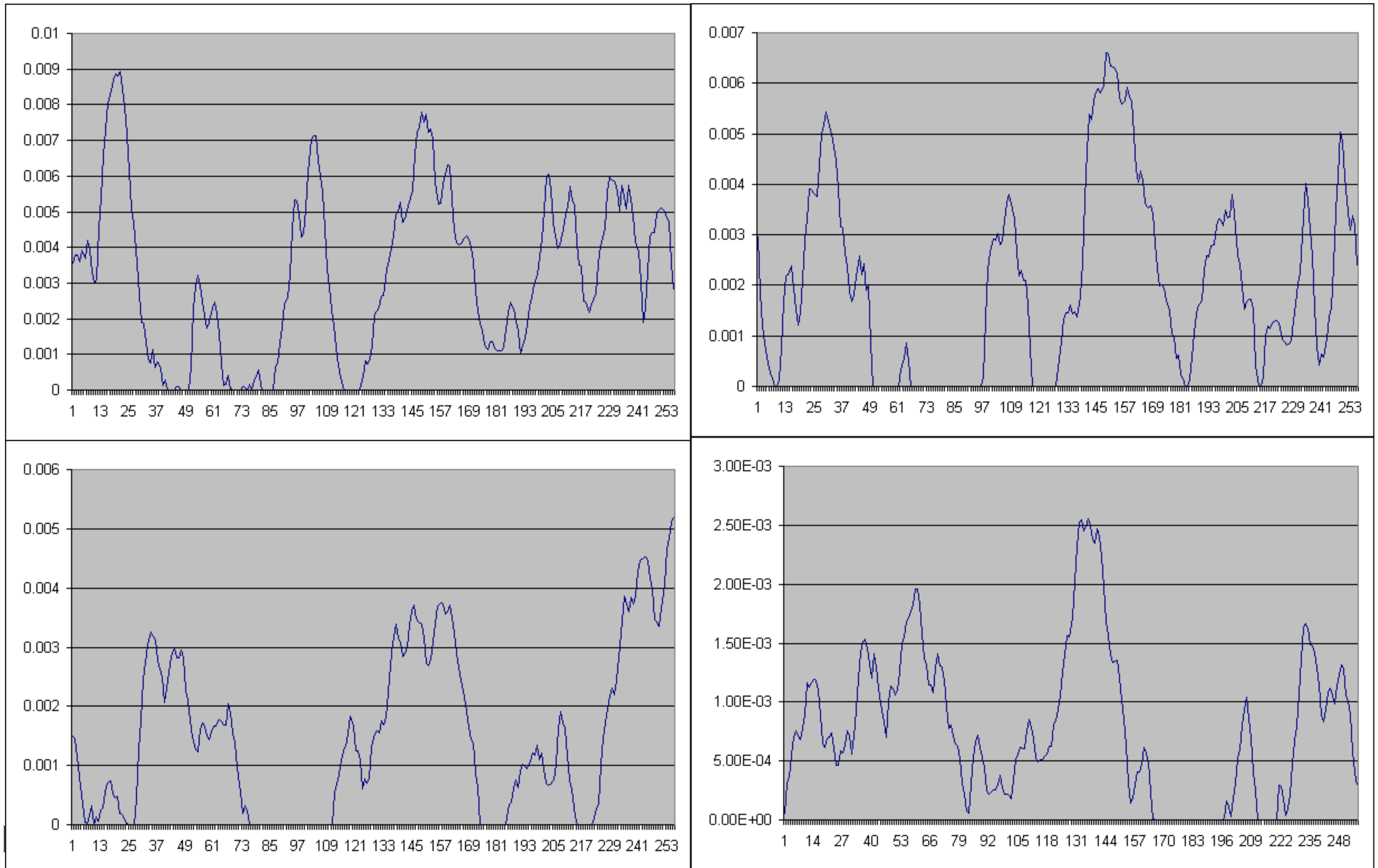
Model Description (2) Correlation Model

- Spatial filtering used to add in spatial correlation
  - Temporal correlation emerges as a side effect
- Smoothing kernels:
  - computed on startup
  - based on image processing methods
- Input length scale determines selection of kernel at each location

Model Output (1) – Downwind Fluctuation Correlation

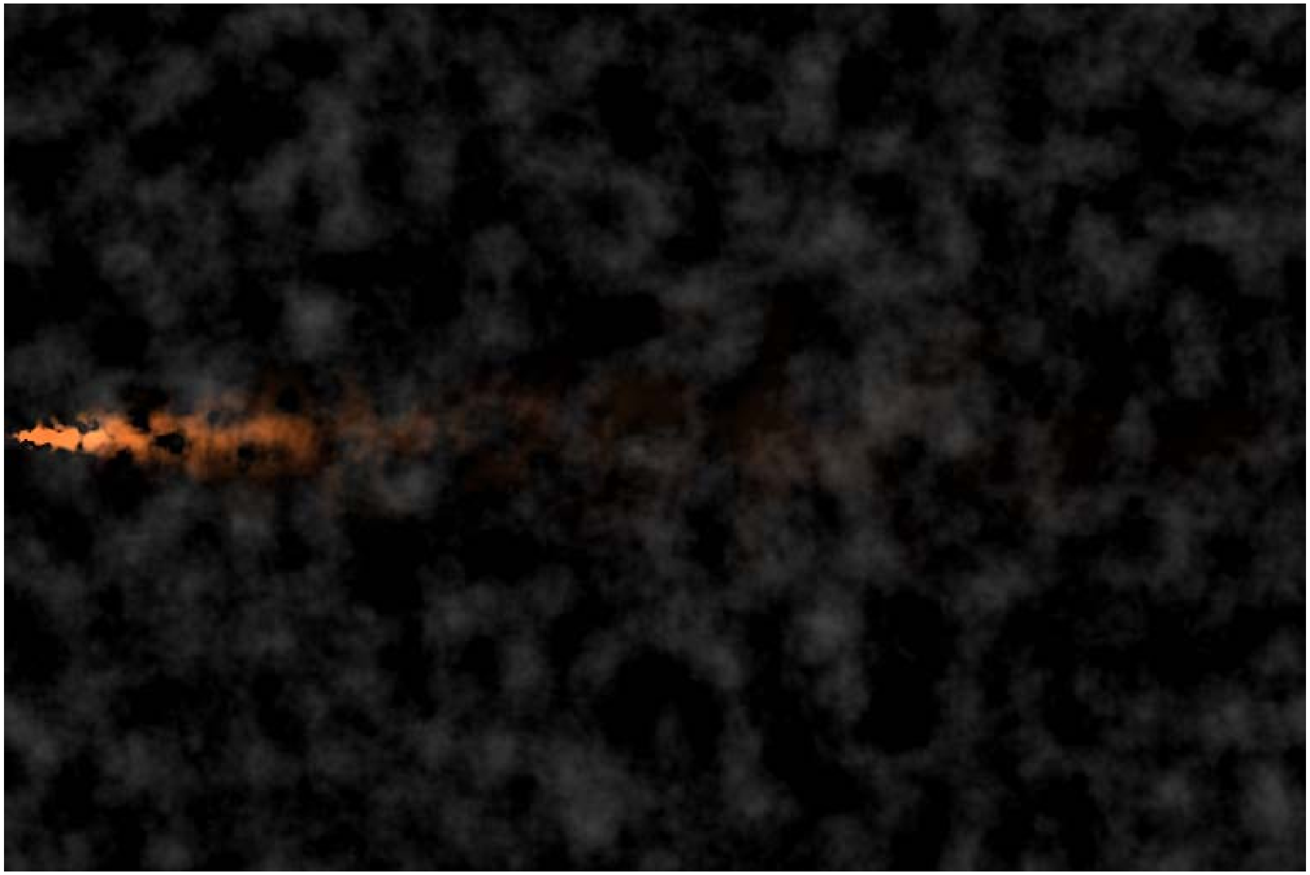


Model Output (2) – Crosswind Fluctuation Correlation



Model Output (3) – Point release with zero background

Model Output (4) – Point release with significant background



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Key advantages

- Based on validated model
- Mean, and variance match the model
- Fluctuations match model predictions
  - Also adds significant refinements
    - Crosswind correlations low
    - downwind correlations high
    - time delay in downwind correlation

Current Model Status

- A standalone software module
  - Developed in pure Java
  - Straightforward system integration path
- Could be used in near-term to create virtual testing solutions for specific systems
  - LIDAR
  - Detector Arrays

Future work (1)

- Use in combination with puff model and a meander model
  - Model would be restricted to synthesizing small-scale correlations giving faster computation
  - Would provide greater fidelity close to source
- Multi-species background modeling
  - With controllable correlation between species
- Extend model to give full 3D fields for some future applications
  - Currently provides a two dimensional slice

Future work (2)

- Hardware implementation of model
  - Compilation down to Field Programmable Gate Array (FPGA) hardware program
  - Enhanced real-time performance
- Embedded implementation in detector hardware (e.g. LIDAR)
  - For system firmware/software evaluation
  - For operator training
  - For exercise support

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Questions?