Back-trajectory Based Methods for Source Parameter Estimation

22 February, 2012

Andrew Annunzio\textsuperscript{1},
Paul E. Bieringer\textsuperscript{1}, George Bieberbach\textsuperscript{1},
Ian Sykes\textsuperscript{2}, Sue Ellen Haupt\textsuperscript{1} and George Young\textsuperscript{3}

\textsuperscript{1}National Center for Atmospheric Research, Boulder CO, USA
\textsuperscript{2}Sage Management, Princeton NJ, USA
\textsuperscript{3}The Pennsylvania State University, State College, PA, USA
Overview of Inverse AT&D Frameworks

- **Eulerian**
  - Model entire concentration field
  \[
  \frac{\partial C}{\partial t} = F(u, u_i, C)
  \]

- **Lagrangian**
  - Lagrangian particle modeling
  \[
  \sum_{i=1}^{N} \frac{dx_i}{dt} = f(x_i, u_i)
  \]
  - Lagrangian puff modeling
  \[
  \sum_{i=1}^{N} \frac{d\bar{x}_i}{dt} = \iiint_{\Omega} Cu_i d\Omega
  \]
Outline

• Basic backward trajectory approach
  – Pure Lagrangian particle trajectory from reversed winds
  – Source determined through particle clustering

• Reverse Eulerian approach
  – Winds reversed
  – Forward model run on reversed winds
  – Source determined in post-processing analysis

• Reverse Eulerian/Lagrangian puff formulation
  – Fit a puff model to sensor observations
  – Determine when spread approaches zero along puff trajectory to infer source location

• Summary
Outline

• Basic backward trajectory approach
  – Pure Lagrangian particle trajectory from reversed winds
  – Source determined through particle clustering

• Reverse Eulerian approach
  – Winds reversed
  – Forward model run on reversed winds
  – Source determined in post-processing analysis

• Reverse Eulerian/Lagrangian puff formulation
  – Fit a puff model to sensor observations
  – Determine when spread approaches zero along puff trajectory to infer source location

• Summary
Basic Backward Trajectory Approach

(Methodology Description)

- Track contaminant filled fluid parcel trajectories backwards in time

- Reverse parcel trajectory originates at the observation location
Basic Backward Trajectory Approach
(Methodology Description)

- Assuming a passive tracer, either numerical weather prediction output or wind observations determine the reverse parcel trajectory.

- The source location is inferred from parcel convergence.
Basic Backward Trajectory Approach
(Strengths and Weaknesses)

• Strengths
  – Can naturally handle multiple release events
  – Approach does not match concentration observations (no optimization necessary)

• Weaknesses
  – Extensive weather observations or high resolution NWP needed for successful source term estimation
  – Not a natural method to determine the source mass
  – Faulty estimates if the flow field in reverse time is divergent
Outline

• Basic backward trajectory approach
  – Pure Lagrangian particle trajectory from reversed winds
  – Source determined through particle clustering

• Reverse Eulerian approach
  – Winds reversed
  – Forward model run on reversed winds
  – Source determined in post-processing analysis

• Reverse Eulerian/Lagrangian puff formulation
  – Fit a puff model to sensor observations
  – Determine when spread approaches zero along puff trajectory to infer source location

• Summary
Reverse Eulerian Approach

Source: $R(x,t)$

Forward Dispersion model: $L$

Sensor data, $d$

Concentration: $c(x,t)$

Inner product $\langle R, c^* \rangle$

Adjoint conc: $c^*(x,t)$

Adjjoint Dispersion model: $L^*$

Sensor: $R^*(x,t)$

Adjoint Dispersion model: $L^*$

Inner product $\langle c, R^* \rangle$
Reverse Eulerian Approach
(with SCIPUFF)

• This Reverse Eulerian approach using SCIPUFF is an informal adjoint technique

\[ \langle (Lc, c^*) \rangle = \langle (c, L^* c^*) \rangle \]

where...

\( Lc \) is related to the source response function, and

\( L^* c^* \) is related to the observations at the sensor locations

• The complexity of SCIPUFF makes calculation of a formal adjoint difficult

• Thus SCIPUFF is run in reverse mode to provide a ‘retroplume’
Reverse Eulerian Approach
(Methodology Description)

CBRN Source Location

CBRN Plume

Triggered Sensors

WIND
Reverse Eulerian Approach

(Methodology Description)
Reverse Eulerian Approach
(Methodology Description)
Reverse Eulerian Approach
(Methodology Description)
Reverse Eulerian Approach
(Post-Processing to Determine Source Term Parameters)

• Source parameter estimate
  – The reverse SCIPUFF calculations produce a hazard area where the source is likely to be located
  – For a source location we can obtain a mass estimate of the contaminant release for each retroplume
    \[ Q_i = \frac{d_i}{c_i^*(x_r)} \]
  – Consistency amongst the mass estimates provides insight on the source location
Reverse Eulerian Approach
(Example with ETEX data)

Source Location Estimate Using Only Sensor Hits

Source Location Estimate Using Sensor Hits and Null Hits

From Sykes 2006

NCAR/RAL - National Security Applications Program
Reverse Eulerian Approach  
(Strengths and Weaknesses)

• **Strengths**
  – Practical, robust framework for source term estimation  
  – Can readily handle multiple contaminant release events  
  – Approach also does not require minimization of a functional  
  – Works seamlessly across a wind range of meteorological scales

• **Weaknesses**
  – Large computational effort is needed for  
    Dense sensor arrays  
    Long duration release  
  – High resolution NWP or meteorological observations are needed, however, not as dense as the traditional Lagrangian approach  
  – Sensitive to faulty measurements
Outline

• Basic backward trajectory approach
  – Pure Lagrangian particle trajectory from reversed winds
  – Source determined through particle clustering

• Reverse Eulerian approach
  – Winds reversed
  – Forward model run on reversed winds
  – Source determined in post-processing analysis

• Reverse Eulerian/Lagrangian puff formulation
  – Fit a puff model to sensor observations
  – Determine when spread approaches zero along puff trajectory to infer source location

• Summary
Eulerian/Lagrangian Puff

- Isolates main STE variables; the contaminant mass, axis and spread
- Determine these variables from contaminant concentration observations
- Determine evolution of these variables in reverse time
- Determine the location where the spread approaches zero
Eulerian/Lagrangian Puff
(Source Estimation Process)

- **Optimization**: Determine mass, location and spread of a puff from surface concentration observations

- **Association**: For multiple release locations associate locations and spread observations with a puff trajectory

- **Estimation**: Determine where the spread approaches zero along the puff trajectory
Example
(Continuous Release Example)
Example
(Continuous Release Example)
Reverse Eulerian Approach
(Strengths and Weaknesses)

• **Strengths**
  – Isolates the variables most crucial for source term estimation (mass, location and spread)
  – Readily handles multiple release events
  – Can infer meteorological forcing variables if sufficient concentration data is present
  – Computationally efficient for single release events

• **Weaknesses**
  – Number of approximating functions constrained by the number of observation locations
  – Requires minimization between approximating function and the concentration observations
  – Complexity increases with multiple source locations, but still more manageable than when working with forward dispersion models
Outline

- Basic backward trajectory approach
  - Pure Lagrangian particle trajectory from reversed winds
  - Source determined through particle clustering

- Reverse Eulerian approach
  - Winds reversed
  - Forward model run on reversed winds
  - Source determined in post-processing analysis

- Reverse Eulerian/Lagrangian puff formulation
  - Fit a puff model to sensor observations
  - Determine when spread approaches zero along puff trajectory to infer source location

- Summary
Summary

• Back trajectory methods seamlessly capture the source term estimation across multiple meteorological scales

• These methods are practical, and are easy to implement

• Information on the source mass requires work in the Eulerian reference frame