

# Ensemble Modeling of Wake Vortices

An overview of ensemble models and ATM considerations

**Nashat Ahmad and Timothy Lewis**

NASA Langley Research Center

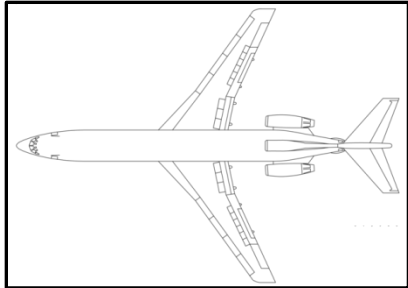
**NASA/DLR Meeting on Wake Vortex Modeling**

**Hampton, Virginia**

**January 17, 2014**

- Fast-Time Wake Models
  - Capabilities
  - Errors
  - Approaches
- Ensemble Modeling
  - Single-Model Ensemble
  - Multi-Model Ensemble
  - As applied to Wake Vortices
- Validation and Verification
- ATM/ATC Applications
  - Our current focus
  - How Wake Vortex knowledge and modeling can make a difference
- Summary/Questions

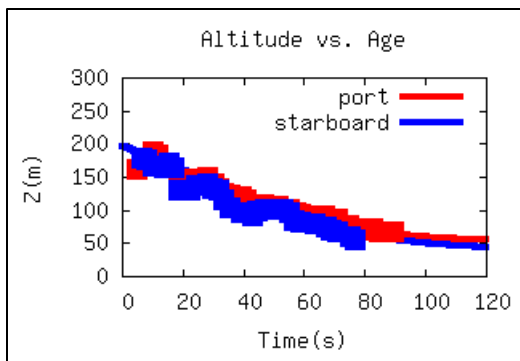
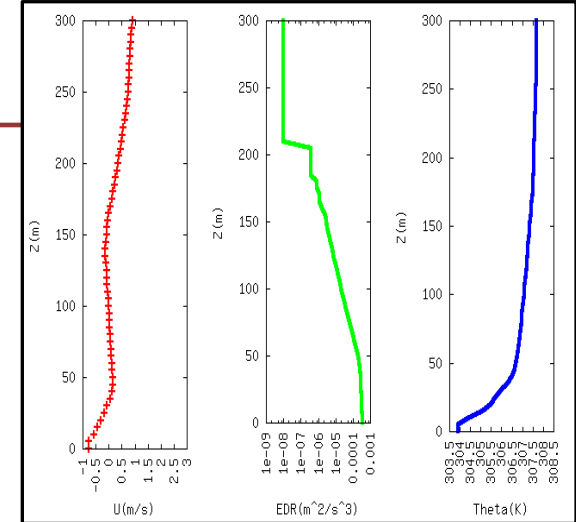
# Fast-Time Wake Models



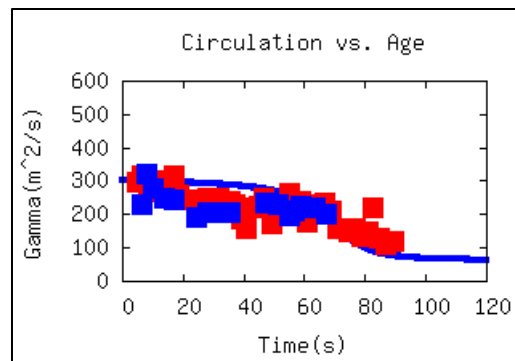
**Atmospheric Conditions**  
Crosswind  
Potential Temperature  
Eddy Dissipation Rate

**Aircraft Parameters**  
Vortex descent velocity,  $V_0$   
Vortex pair separation,  $b_0$

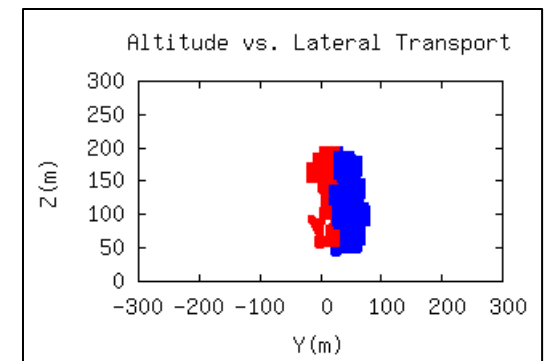
**Fast-Time Wake Vortex Models**



**Vortex Pair Descent**

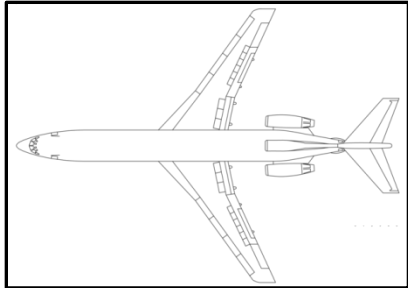


**Vortex Pair Decay**



**Lateral Transport**

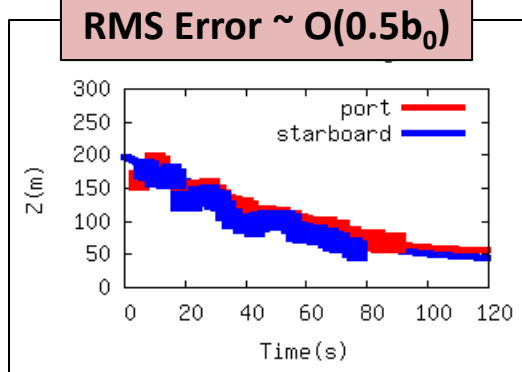
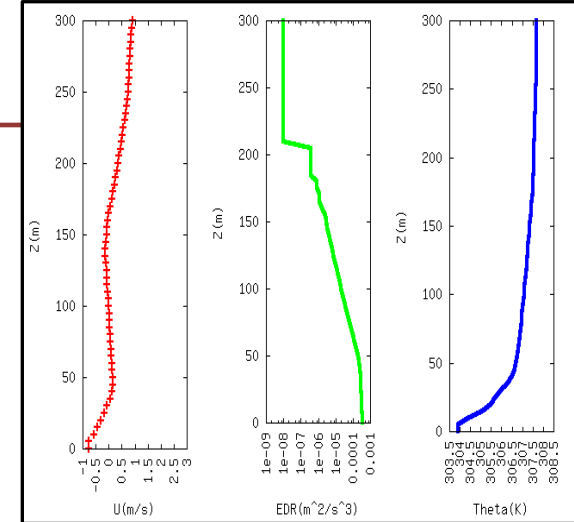
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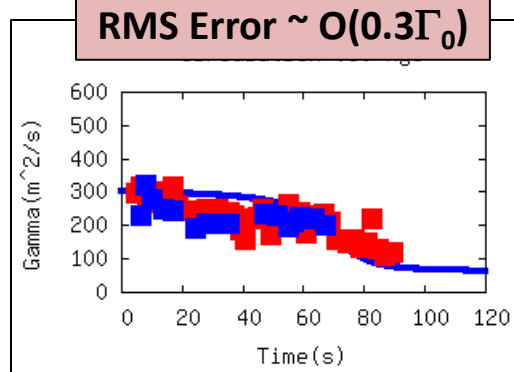
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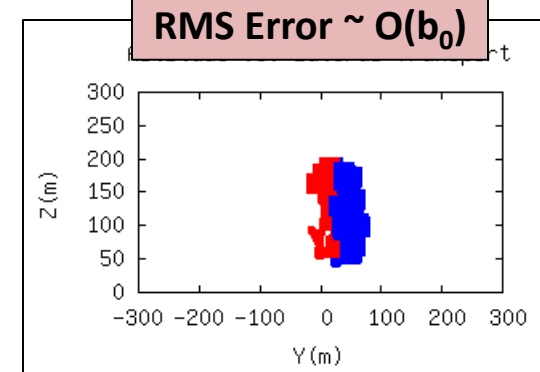
**Fast-Time Wake Vortex Models**



**Vortex Pair Descent**



**Vortex Pair Decay**



**Lateral Transport**

- Initial Conditions
  - Data
    - Sensor errors
    - Insufficient resolution (spatial and temporal)
  - Data Processing
    - Algorithms (e.g., data fusion methods)
    - Coding errors
- Model
  - Incomplete physics
  - Algorithms (e.g., numerical schemes)
  - Insufficient spatial and temporal resolution
  - Coding errors

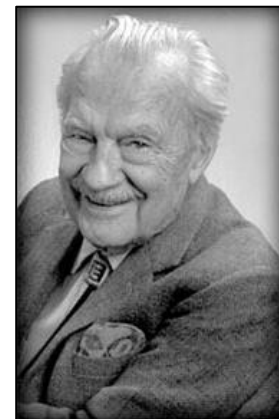
- Methods based on simulations of physical models using different perturbations in initial conditions
- Numerous Applications, e.g.,
  - Uncertainty Quantification
    - Risk Analysis
    - Weather Forecasting
  - Numerical Integration



**Stanislaw Ulam**  
(1909-1984)



**John von Neumann**  
(1903-1957)

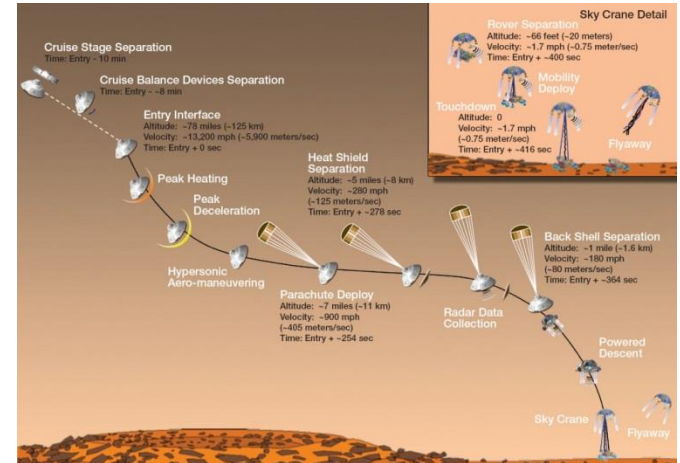


**Nicholas Metropolis**  
(1915-1999)

# Monte-Carlo Methods



- Methods based on simulations of physical models using different perturbations in initial conditions
- Numerous Applications, e.g.,
  - Uncertainty Quantification
    - Risk Analysis
    - Weather Forecasting
  - Numerical Integration



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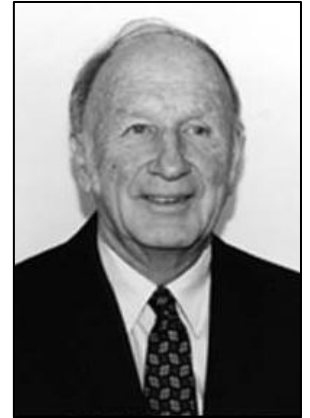


**John von Neumann**  
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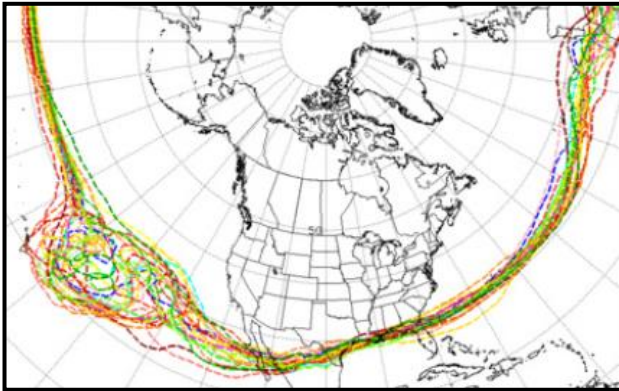
- Extensive application in the field of Numerical Weather Prediction
- Lorenz
  - Analysis of error growth
  - Even if we assume that a physical process is perfectly understood, there is a limit on predictability due to incomplete knowledge of initial conditions
- Leith
  - Monte Carlo ensemble
  - “If the initial state were known exactly and if the model exactly simulated the atmosphere, then the computed phase path would provide an exact forecast. But neither assumption is valid.”



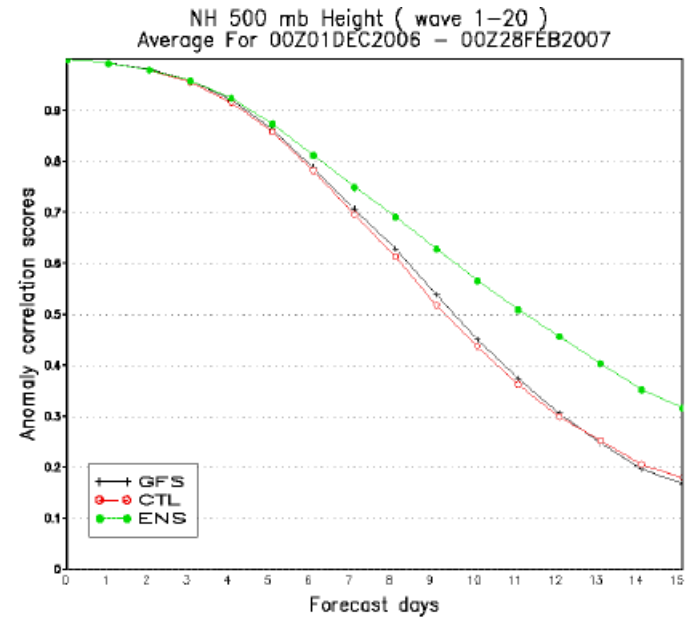
**Edward N. Lorenz**  
(1917-2008)

- Single-Model Ensemble
  - Errors in initial conditions dominate the solution
    - Lyapunov vectors (mathematical basis)
    - Singular vectors (all initial errors have same contributions)
    - Bred vectors (previous forecast can indicate initial errors)
- Multi-Model Ensemble
  - Single model with varying physics options
  - Different models
    - Assumption is that some models may have the ability to represent certain physical processes more accurately than other models
    - If all members are inaccurate, the ensemble is not an improvement
  - Multi-model ensembles have no mathematical basis and are based on heuristics

# Ensemble Modeling (NWP)



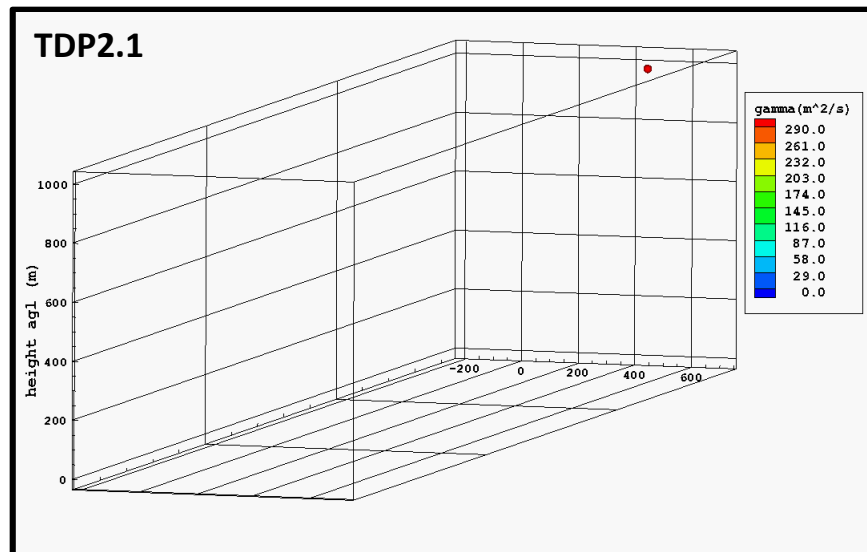
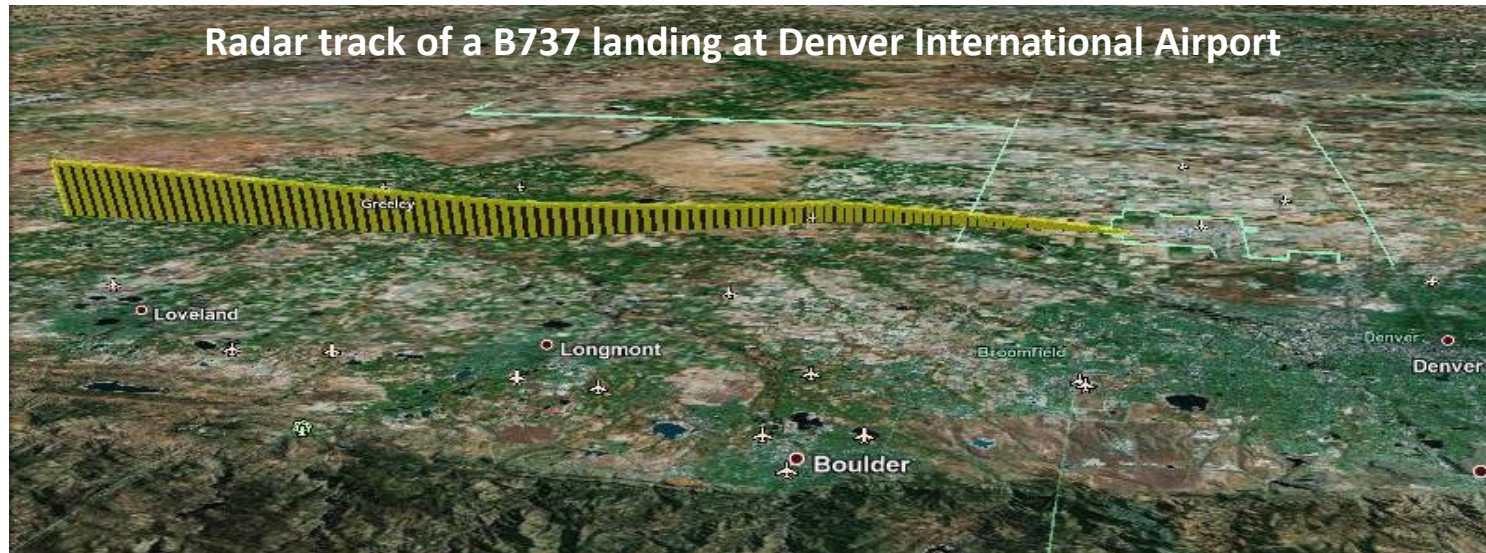
Peña (2011)



- Multi-Model Ensemble

- Single model with varying physics options
- Different models
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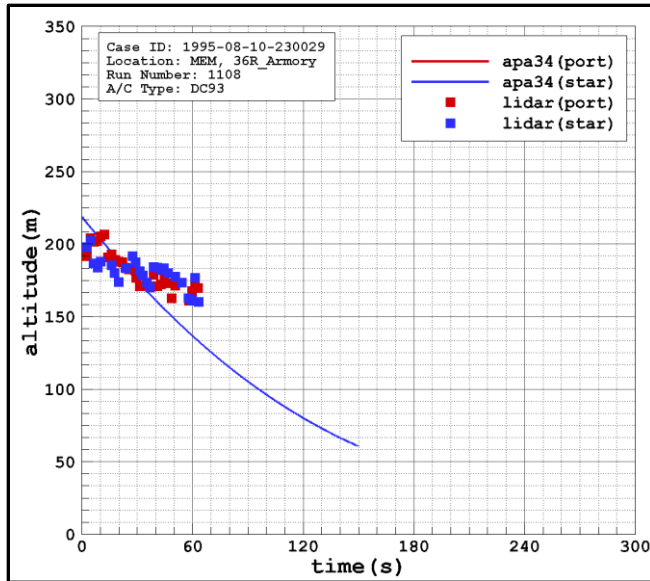
# Ensemble Modeling



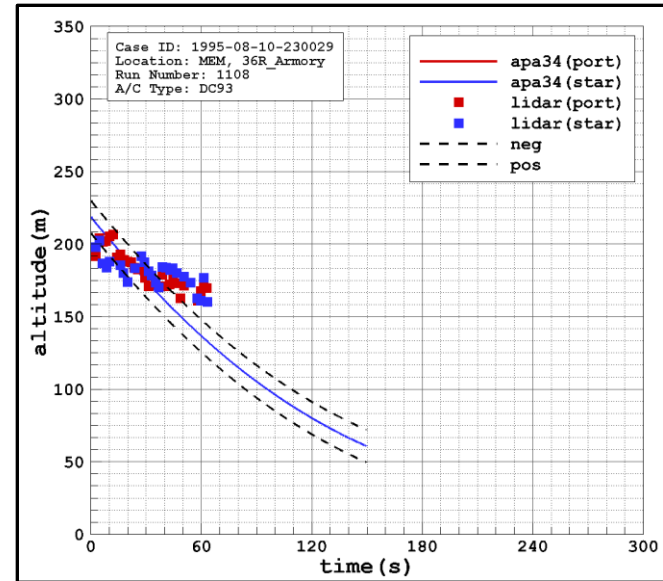
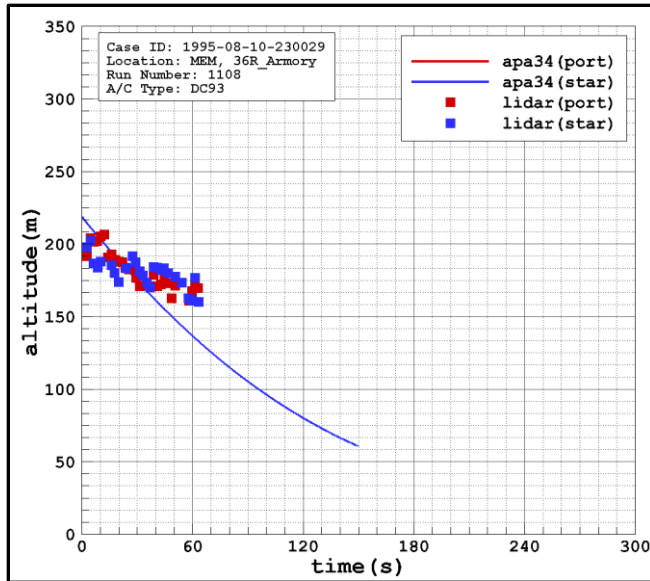
$$V_0 = 2.052 \text{ m/s}$$
$$b_0 = 22.7 \text{ m}$$

$$N = 0.01 \text{ s}^{-1}$$
$$\varepsilon = 10^{-5} \text{ m}^2/\text{s}^3$$
$$U = -1, 0, 1 \text{ m/s}$$

# Ensemble Modeling

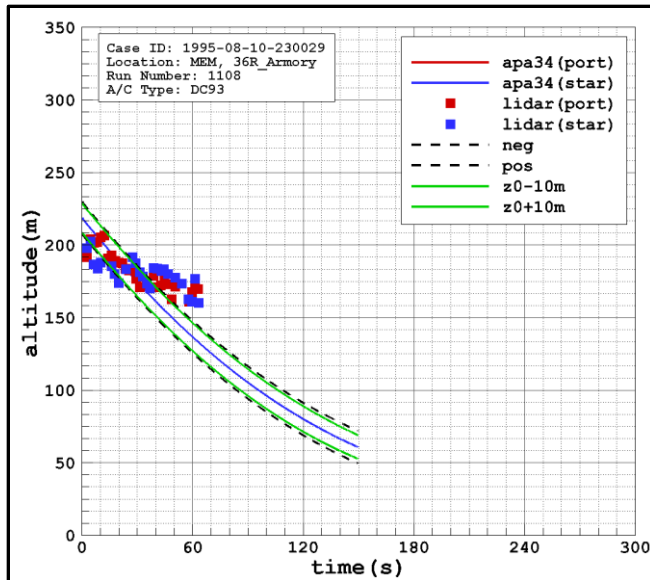
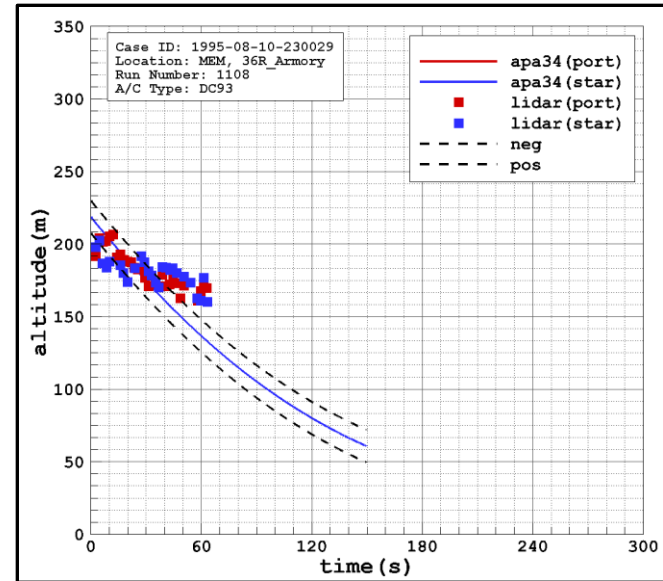
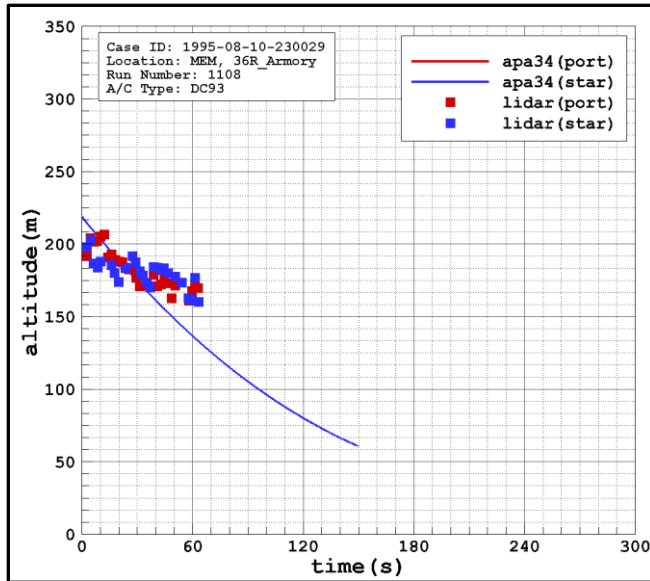


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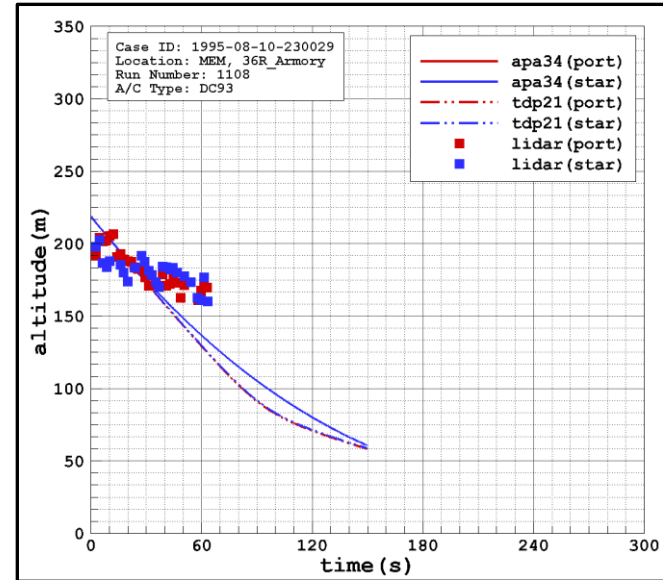
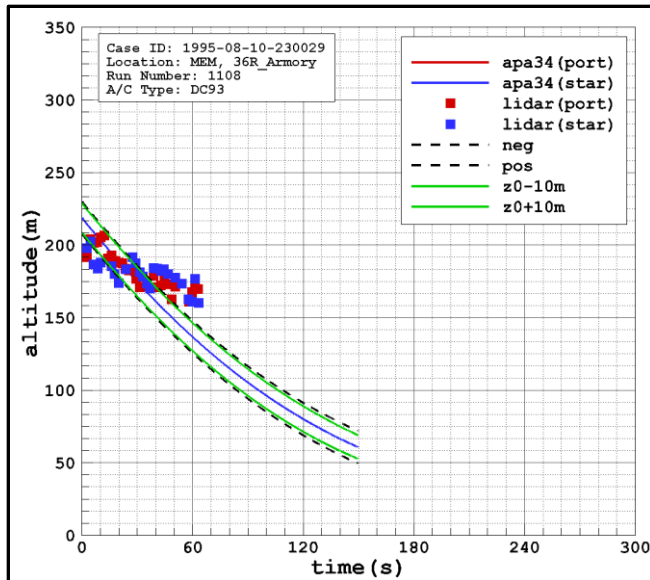
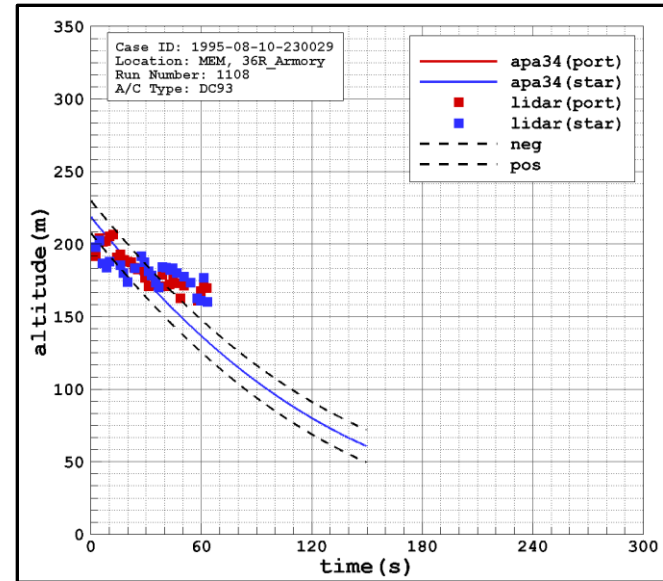
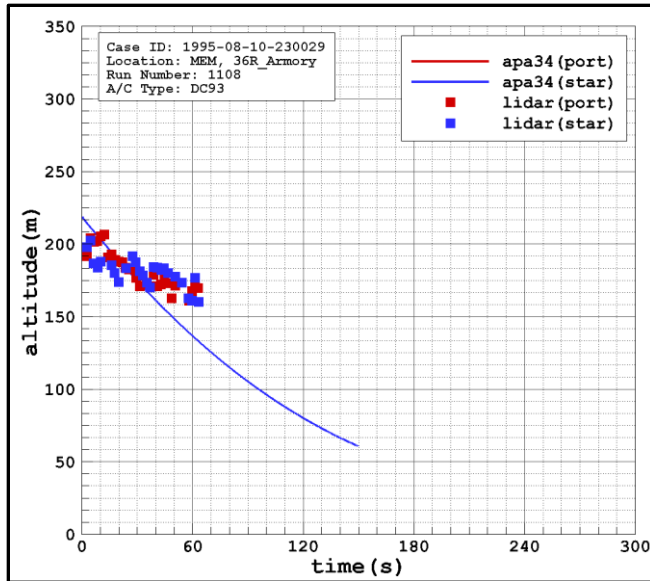
Bounded by  $0.5b_0$   
(RMSE in altitude)

# Ensemble Modeling

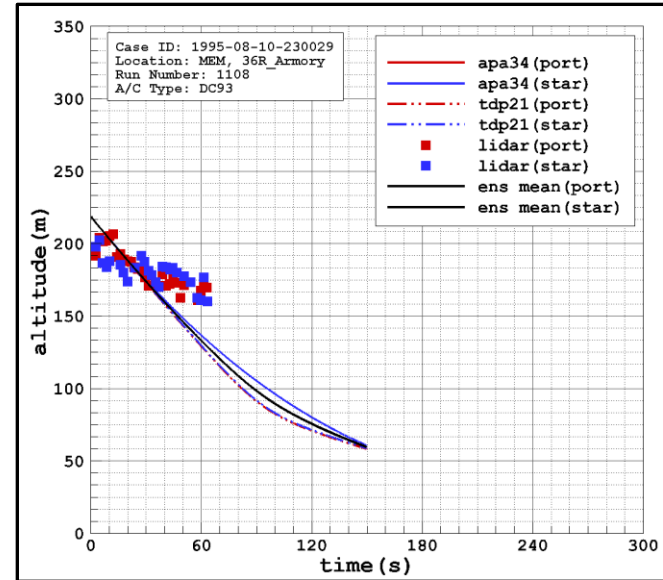
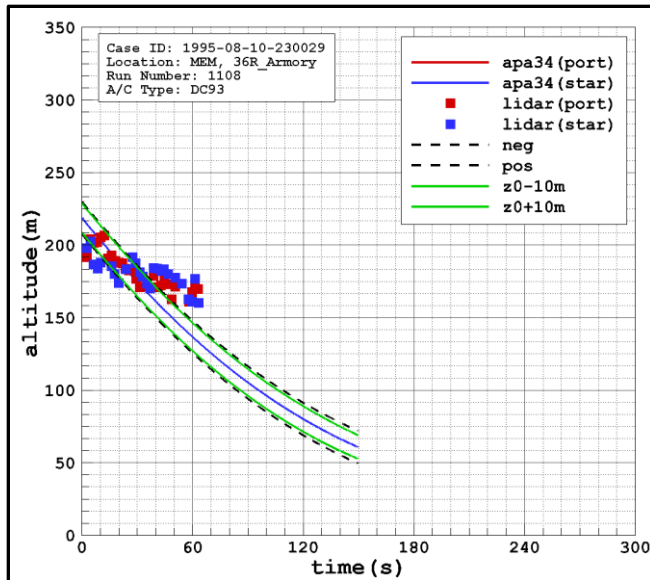
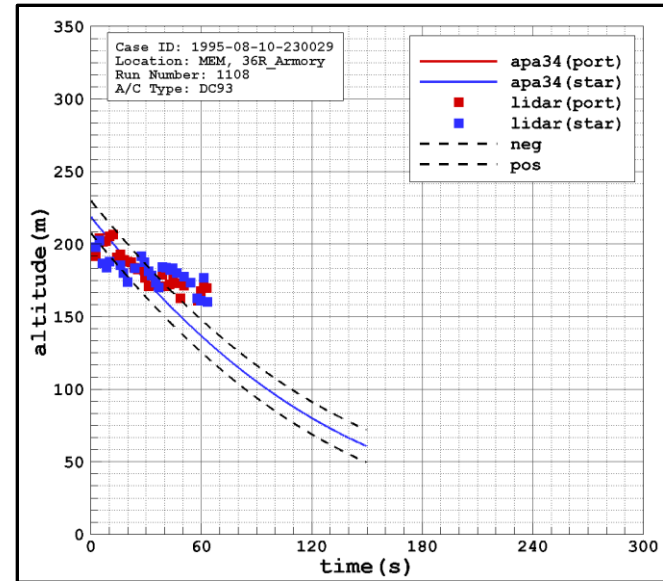
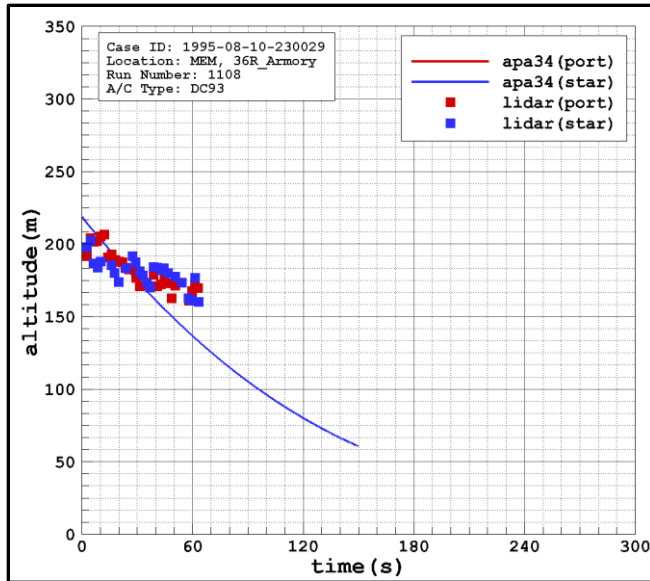


Perturbations added in  $z_0$  ( $\pm 10\text{m}$ )

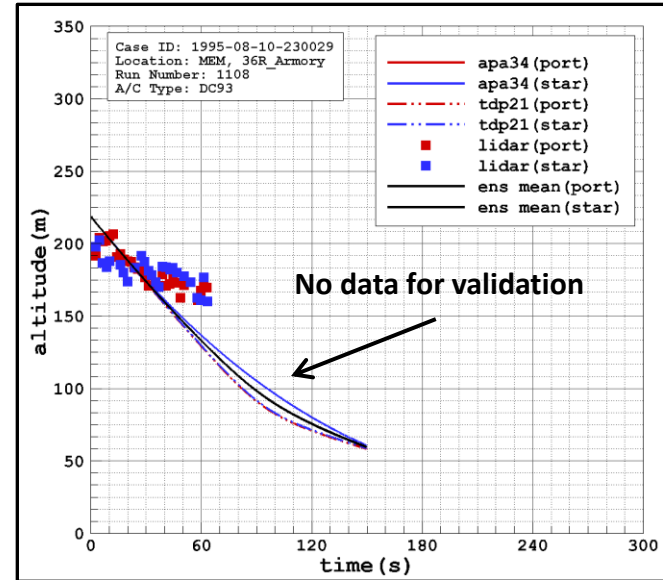
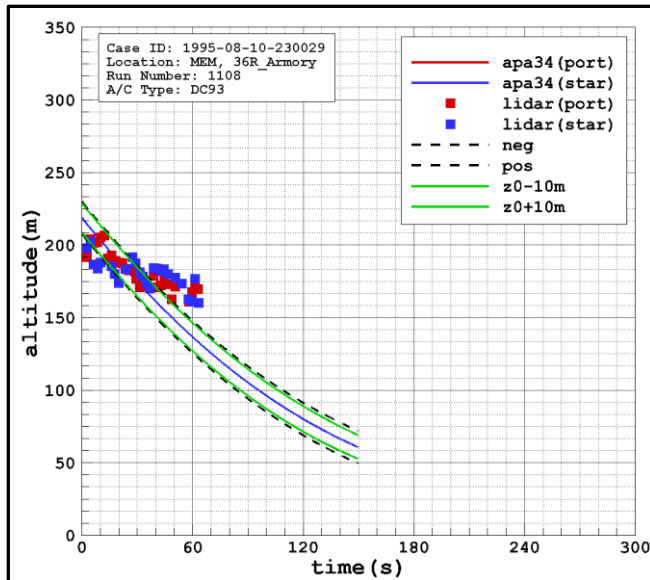
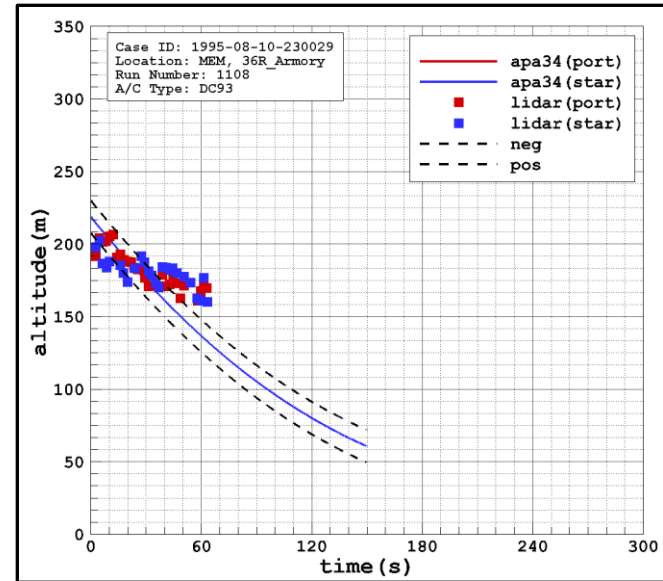
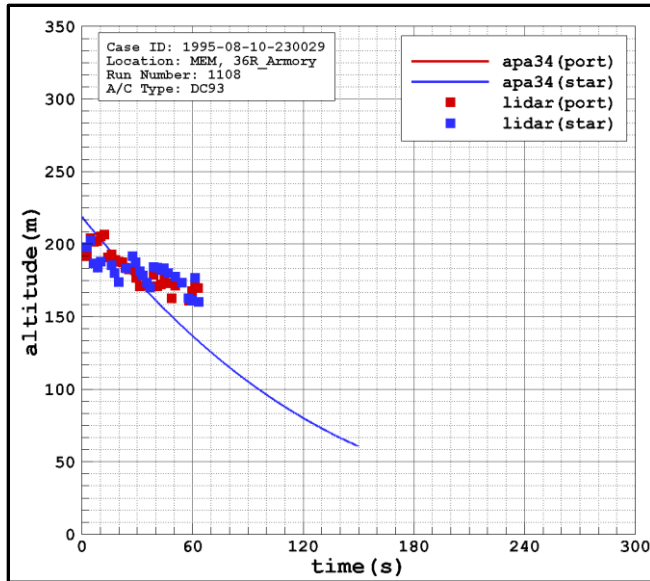
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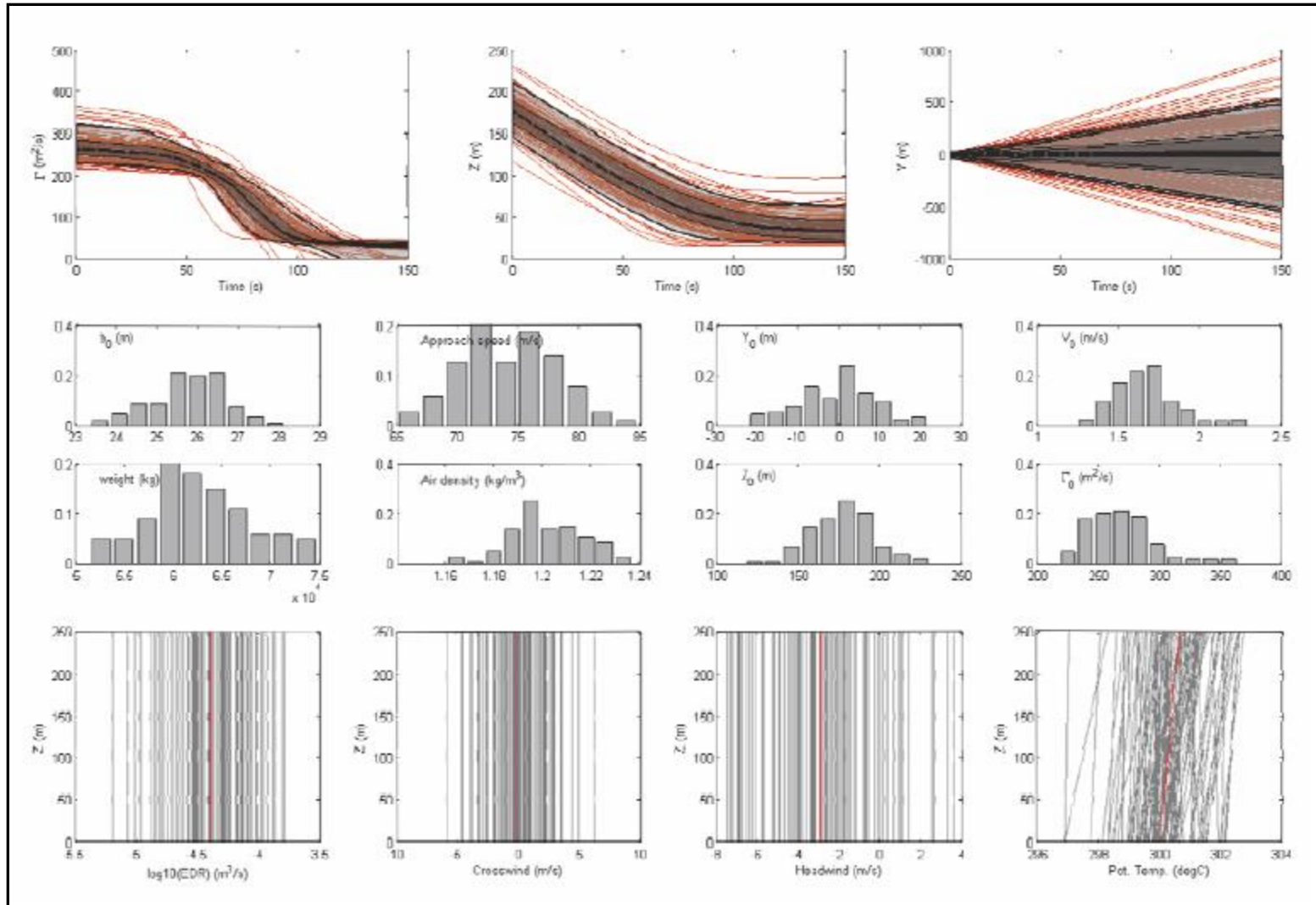
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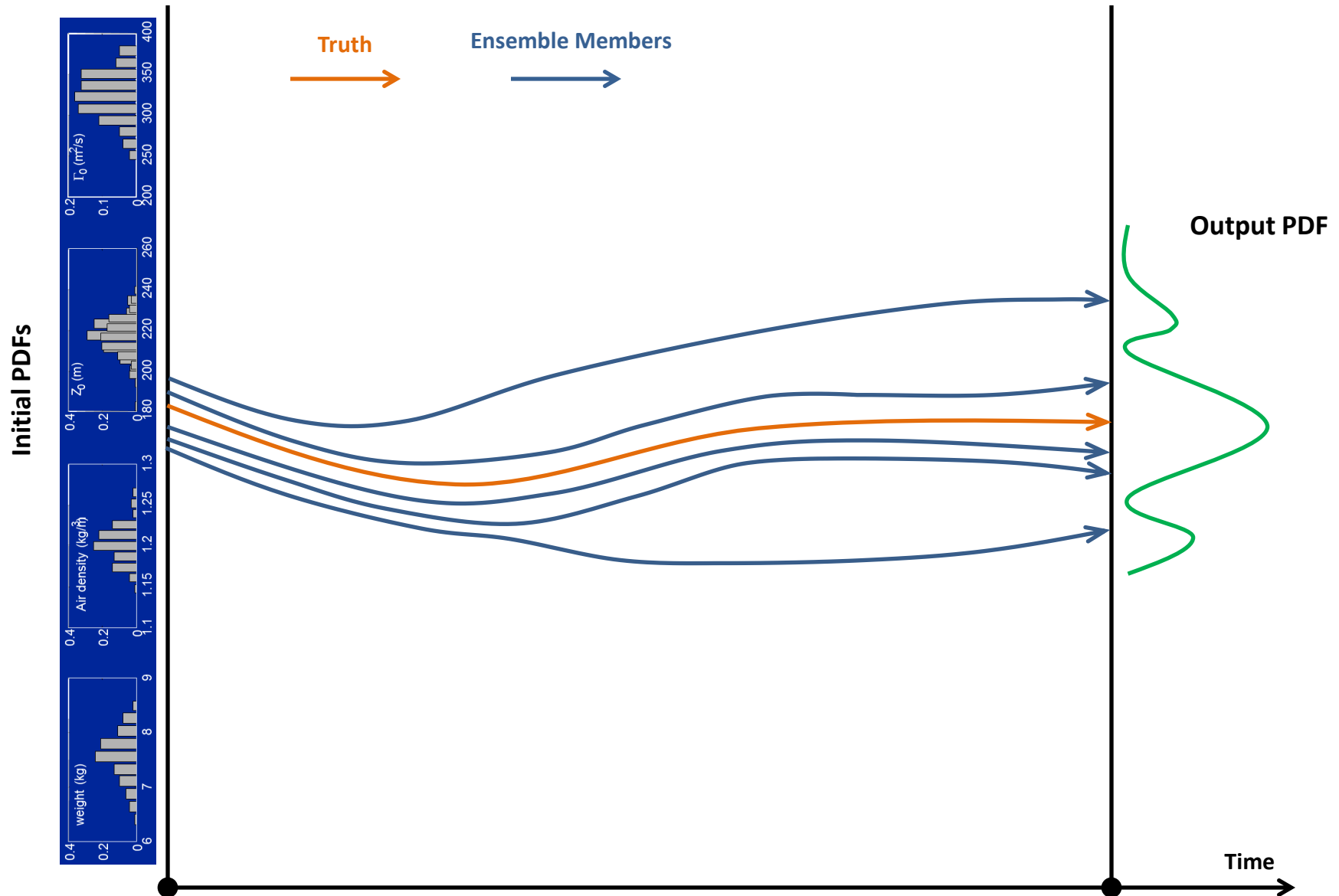
# Wake Research and Prediction System (WRAPS)



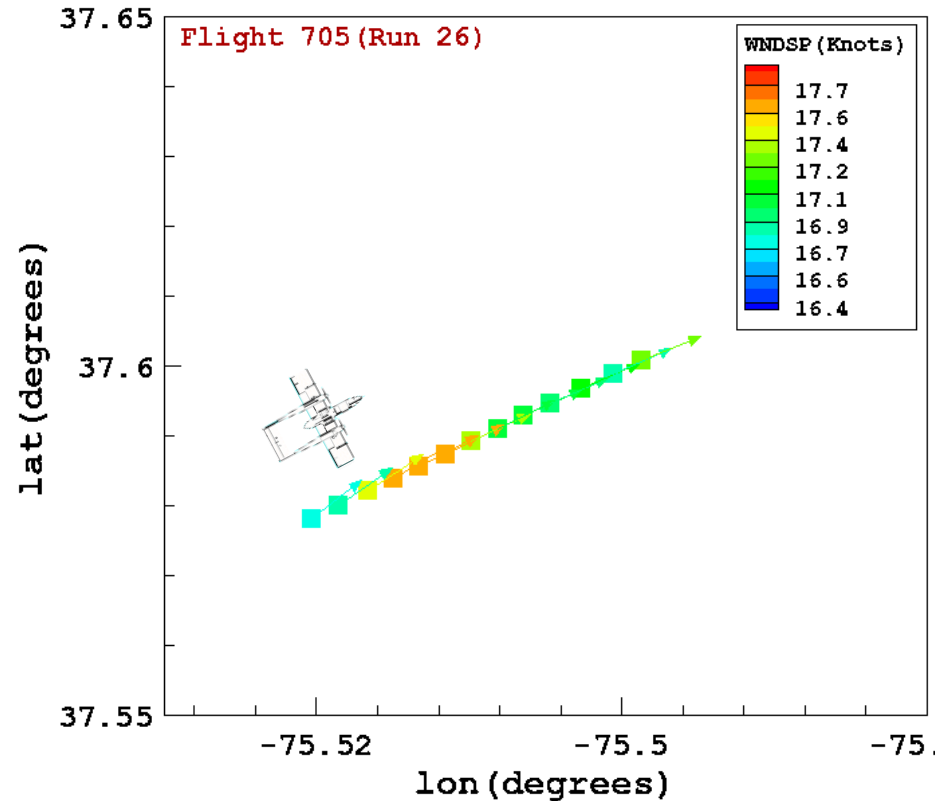
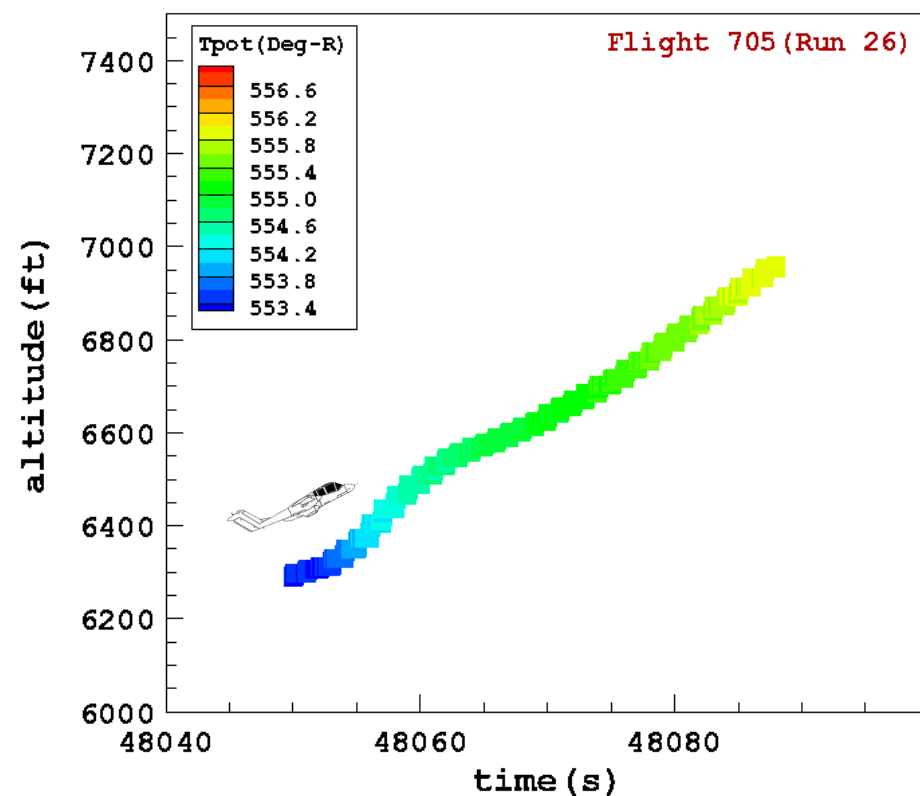
**Pruis and Delisi (2011)**

NASA NRA: Enabling Super-Dense Operations by Advancing the State of the Art of Fast-Time Wake Vortex Modeling

# Ensemble Modeling



# Validation and Verification



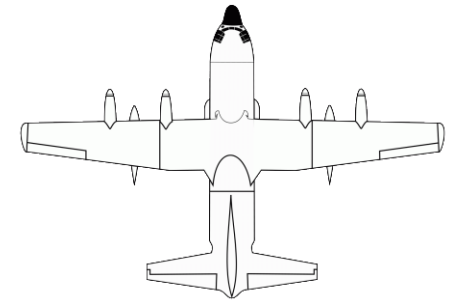
| Flight | Altitude (ft) | Weather                          | $\varepsilon$ (ft <sup>2</sup> /s <sup>3</sup> ) | $N$ (s <sup>-1</sup> ) | Wake Summary                                       |
|--------|---------------|----------------------------------|--------------------------------------------------|------------------------|----------------------------------------------------|
| 705    | 6200-8000     | Hazy<br>low turbulence<br>stable | 0.00002                                          | 0.01-0.015             | Very small oscillations<br>Onset of Crow after 5nm |

Vicroy et al. (1998)

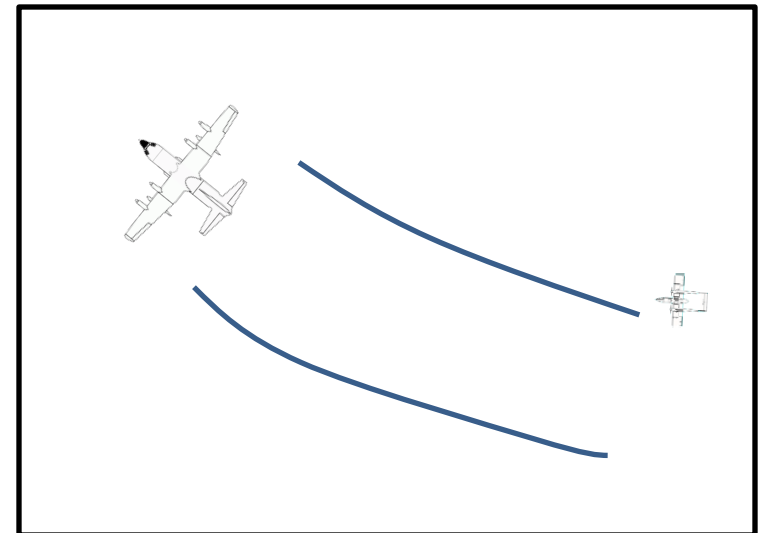
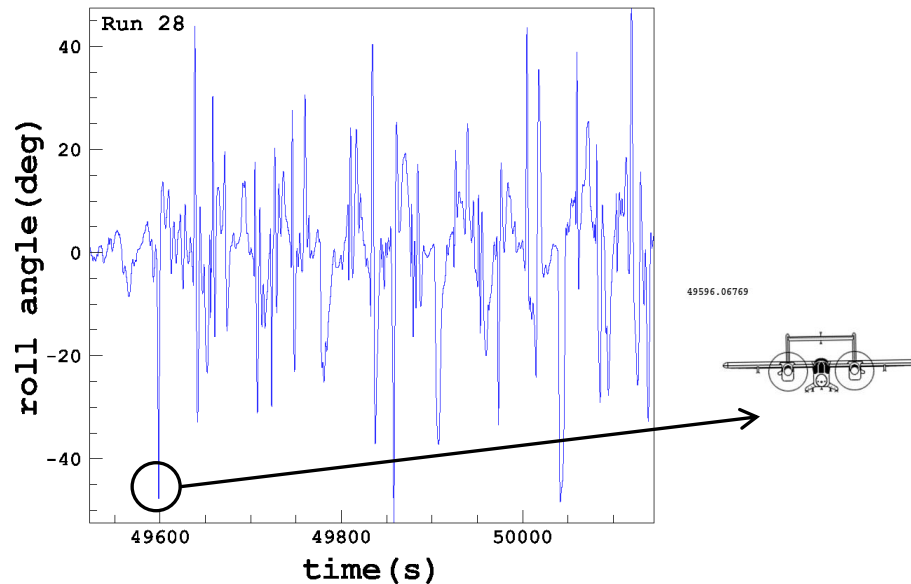
## Flight 705

| Run | $\Gamma_0 (=W/b_0\rho U)$ ft <sup>2</sup> /s | $V_0 (= \Gamma_0/2\pi b_0)$ ft/s | $T_* (=b_0/V_0)$ s |
|-----|----------------------------------------------|----------------------------------|--------------------|
| 27  | 2123                                         | 3.2                              | 32.0               |
| 28  | 2206                                         | 3.4                              | 30.8               |
| 29  | 1482                                         | 2.3                              | 45.8               |
| 30  | 1464                                         | 2.2                              | 46.4               |
| 37  | 2033                                         | 3.1                              | 33.4               |

Vicroy et al. (1998)



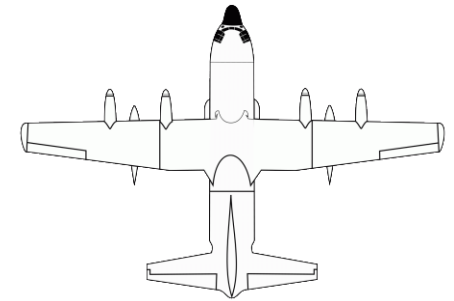
$b_0 = 104$  ft



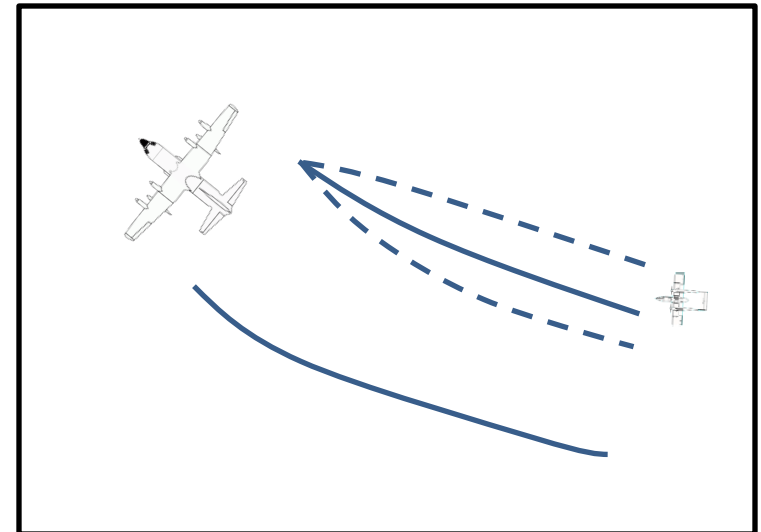
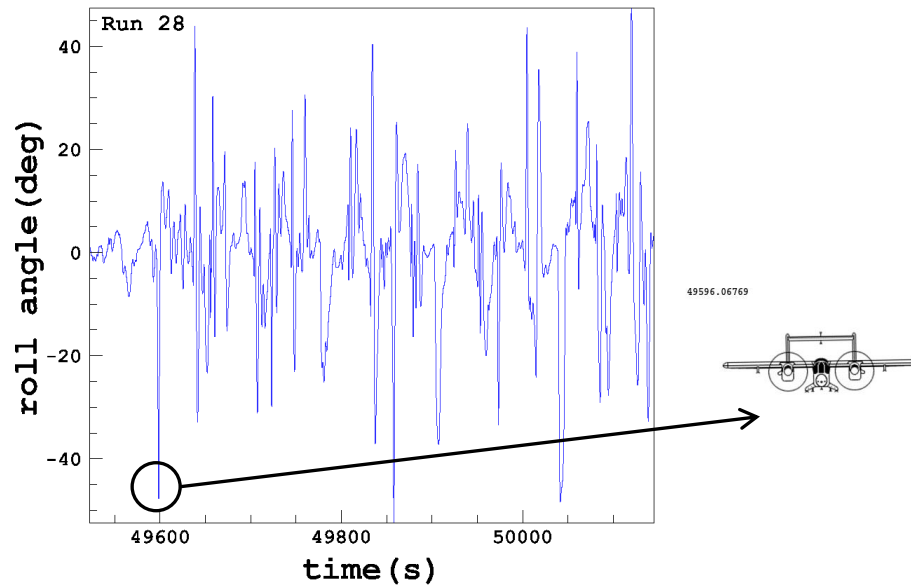
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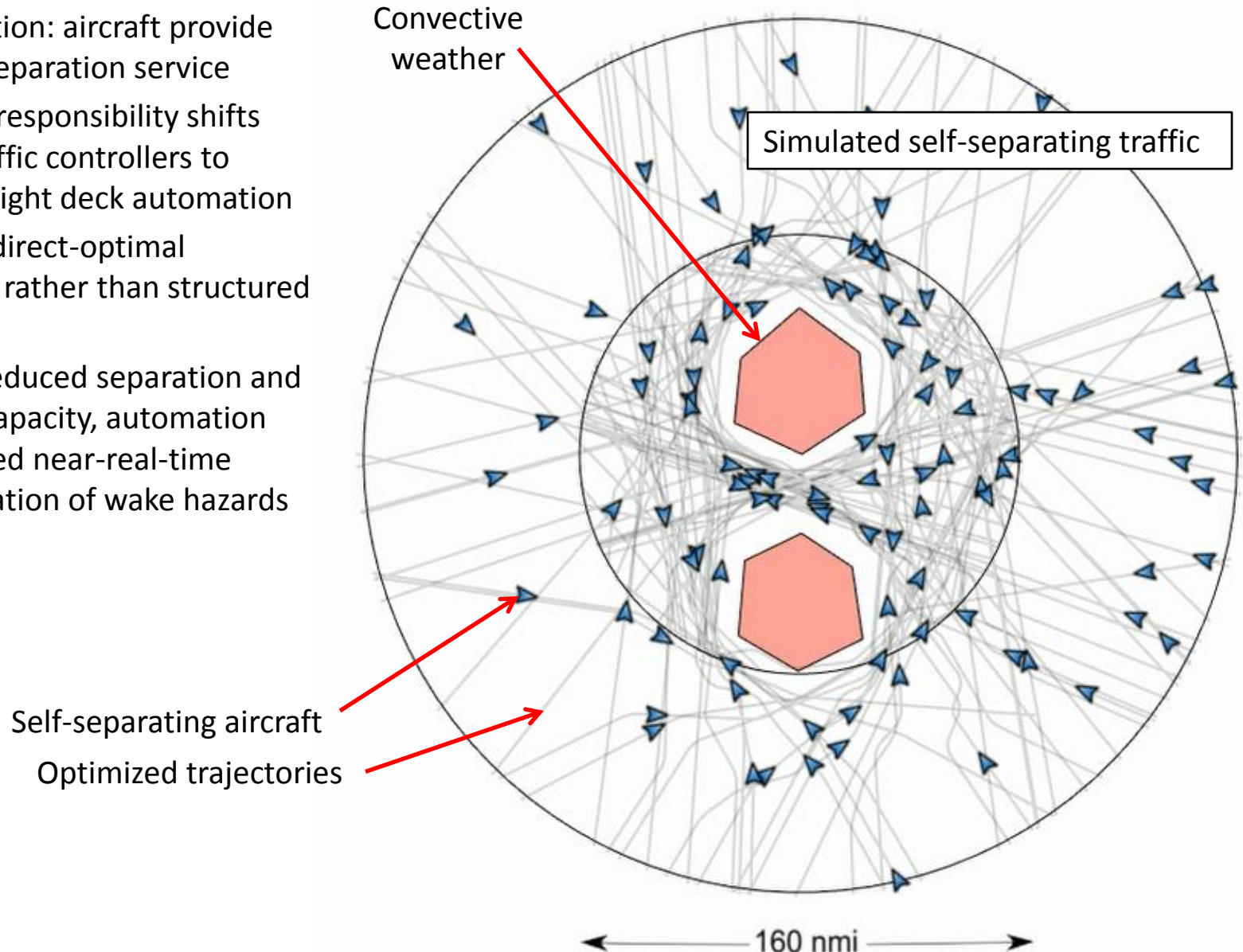


# **Air Traffic Management applications**

# Advanced Self-Separation ConOps



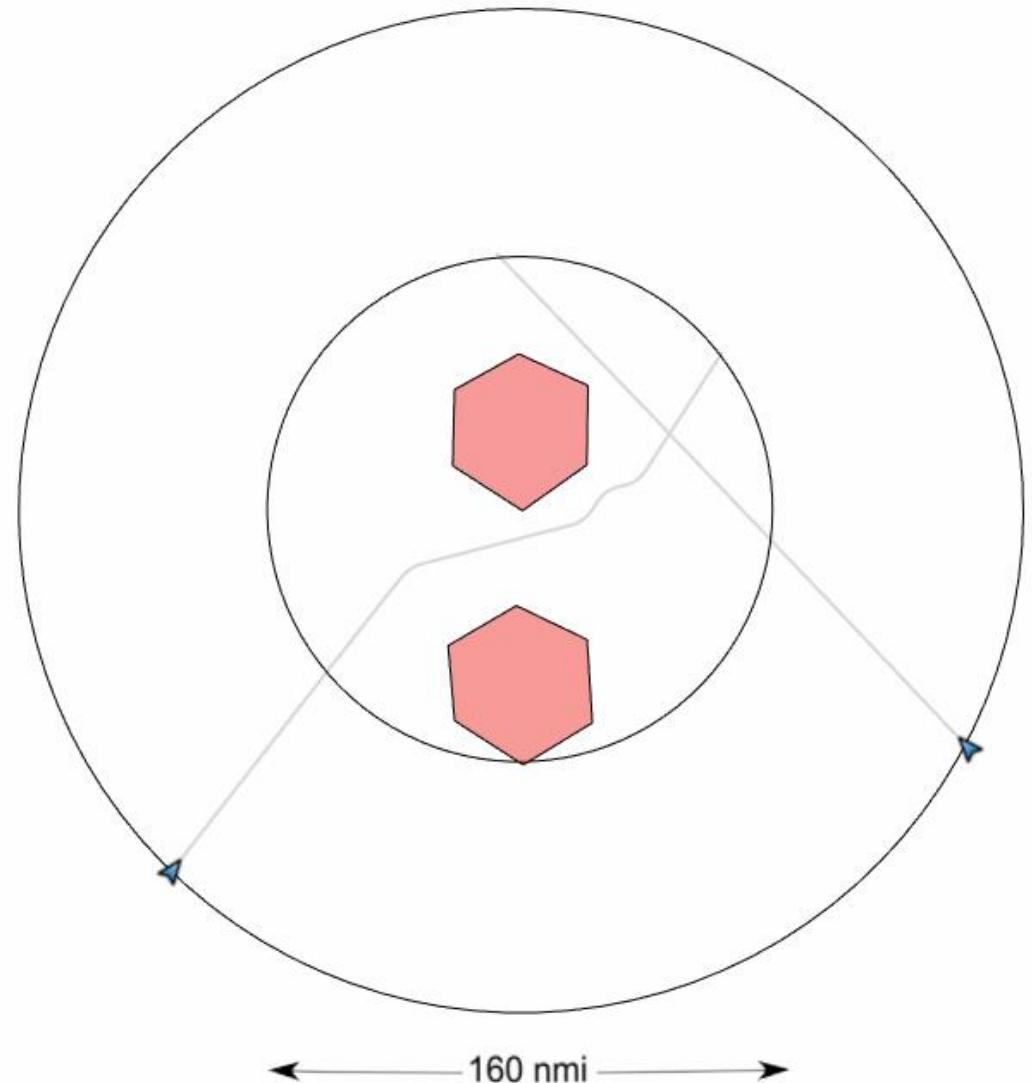
- Self-separation: aircraft provide their own separation service
- Separation responsibility shifts from air traffic controllers to pilots and flight deck automation
- Aircraft fly direct-optimal trajectories rather than structured routes
- To realize reduced separation and increased capacity, automation systems need near-real-time characterization of wake hazards



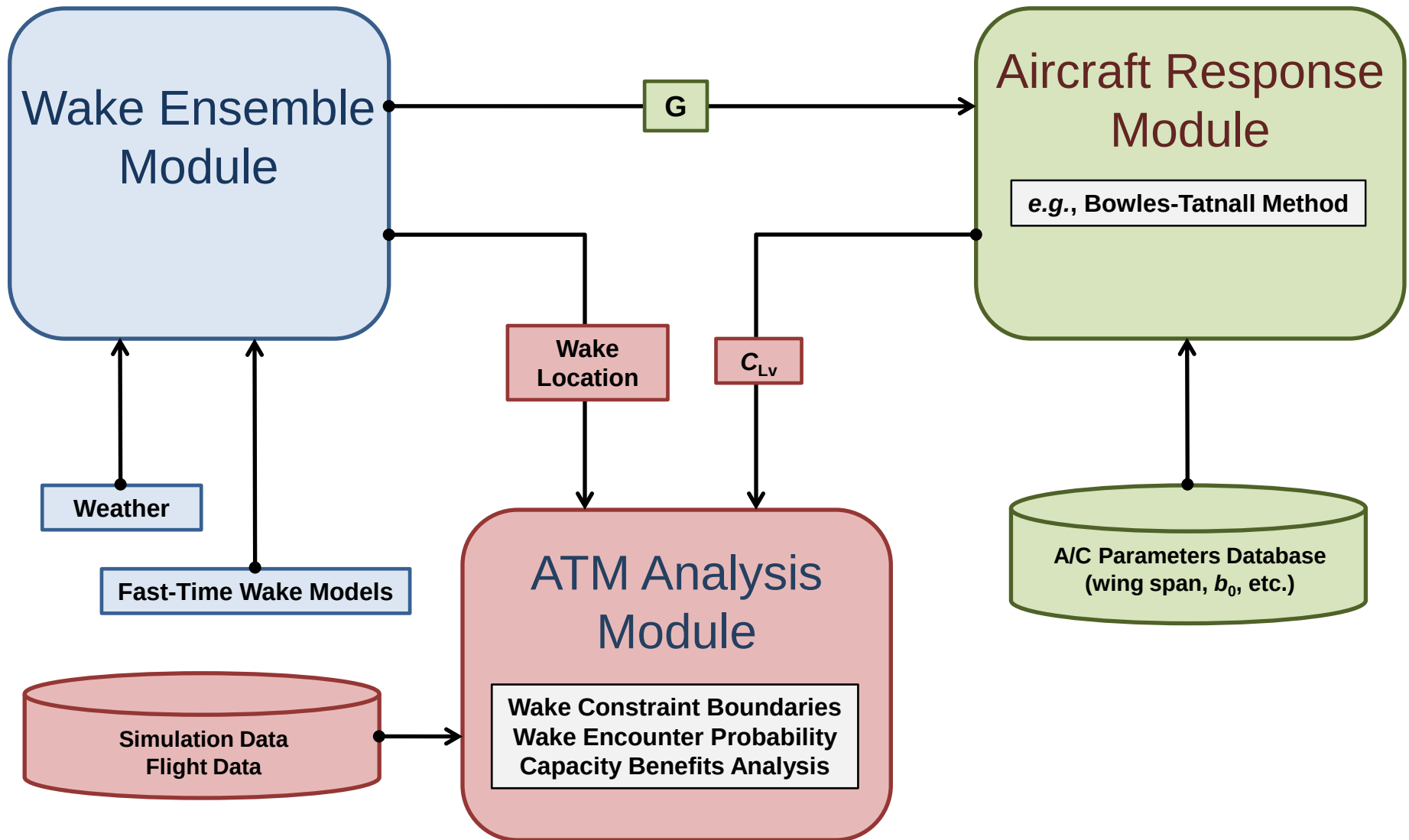
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# Aircraft Wake Analysis System



- Data requirements
  - What is the amount of data required to generate the initial PDFs?
- Methodology
  - Monte Carlo would be useful for defining wake constraints in the design of new ATM/ATC concepts but may not be feasible for use as an on-board tool
- Output
  - Methods for generating outputs PDFs
- Validation and Verification
  - Data
    - Lidar observations
    - Wake encounter data
  - Metrics (Reliability, Skill, etc.)
- ATM Requirements
  - Integration of wake models into ATM/ATC concepts development
  - Aircraft dependent wake hazard definition?
  - Computational constraints

- Bacon, D.P., “To Ensemble – Or Not To Ensemble”, Atmospheric Dispersion and Transport Modeling Workshop, George Mason University, 2000.
- Holzäpfel, F., “Sensitivity Analysis of the Effects of Aircraft and Environmental Parameters on Aircraft Wake Vortex Trajectories and Lifetimes”, AIAA Paper 2013-0363.
- Kalnay, E., “Atmospheric Modeling, Data Assimilation and Predictability”, Cambridge University Press. 2003.
- Leith, C.E., “Theoretical Skill of Monte Carlo Forecasts”, *Monthly Weather Review*, Vol. 102, 1974, pp. 409-418.
- Lorenz, E.N., “The predictability of a flow which possesses many scales of motion”, *Tellus*, Vol. 21, 1969, pp. 289-307.
- Peña, M., “Ensemble Forecasts and their Verification”, AOSC 630 Class Notes.
- Pruis, M.J., D.P. Delisi, “Comparison of Ensemble Predictions of a New Probabilistic fast-Time Wake Vortex Model and Lidar Observed Vortex Circulation Intensities and Trajectories”, AIAA Paper 2011-3036.
- Sivillo, J.K., J.E. Ahlquist, Z. Toth, “An Ensemble Forecasting Primer”, *Weather Forecasting*, Vol. 12, 1997, pp. 809-818.
- Vicroy, D.D., P.M. Vijgen, H.M. Reimer, J.L. Gallegos, P.R. Spalart, “Recent NASA Wake-Vortex Flight Tests, Flow Physics Database and Wake-Development Analysis”, AIAA Paper 1998-5592.

# Air Traffic – Northeastern United States

