Development of a New Probabilistic Wake Vortex Prediction Model

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Acknowledgments

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- The work was performed under the NASA NRA “Enabling Super-Dense Operations by Advancing the State of the Art of Fast-Time Wake Vortex Modeling”
- The lidar data shown in this study was provided by NASA
- The Federal Aviation Administration (FAA) has also provided lidar data to use in comparison studies and also provided funding for several of the models that have been incorporated in the new probabilistic model
- Current funding for this work is under the NASA NRA “Wake Vortex Data Collection for Robust Modeling Validation to Enable Advanced, NextGen, Wake-Conscious, Capacity-Enhancing Concepts”
- Neil O’Connor and Dr. Fred Proctor are the technical monitors
Motivation

What did we do? and What did we find out?

Next Steps

Discussion on related scientific questions, and the feasibility and priorities of different methods with respect to future research.
Goal of NASA Probabilistic Model

Quantify the probability of finding a vortex at a specified location at a specified time after passage of a known aircraft in a known atmosphere, where the vortex is of a specified strength or greater.
Why is a Fast-time Probabilistic Model Needed?

• Large number of model inputs
  • All model inputs have uncertainties
    • Interaction of these uncertainties and affect of uncertainties on the model predictions is not obvious

• Not clear there is a “best” deterministic fast-time wake vortex prediction model

• Uncertainties in observations are poorly quantified
Suboptimum weather information

a) Uncertainties in meteorological sensing
b) Nonhomogeneity of weather conditions
c) Changes in weather since time of last observation
Uncertainties in aircraft parameters, e.g., position

Also,
- aircraft weight
- true air speed
- initial vortex spacing
- time of overflight

Shown is the 95% confidence intervals estimated from the maximum standard deviations for each distance from the threshold reported in
Ambiguities due to model assumptions, simplifications, and parameterizations

Environmental Conditions

Out-of-Ground Effect

In-Ground Effect

Environmental Conditions

N* = 0

N* = 0.25

EDR* = 0.1

N* = 0.5

N* = 1
Uncertainties in the observation of wakes

- Mean biases of the wake observations with LCMT pulsed lidar are
  - 2-4 m in vertical
  - 4-8 m in horizontal

Environmental Parameters
- air density(z)
- crosswind(z)
- headwind(z)
- EDR(z)
- potential temperature(z)

Aircraft Parameters:
- aircraft weight
- air speed
- initial vortex spacing
- initial lateral position
- initial vertical position

Deterministic Fast-time Wake Vortex Prediction Model

Used for Model Assessment and Calibration (Model Improvement)

Estimates of Wake Vortex Transport and Decay

Observations
Wake Research And Prediction System (WRAPS)

— Ensemble of deterministic, fast-time wake vortex prediction models
— Input uncertainties (i.e., a/c position and speed, weather) are included using a Monte-Carlo approach
— Allows user to compare with wake data that was obtained under similar conditions

How is this model different?

● Principal difference between the new NASA probabilistic model and other probabilistic models is that it is an ensemble of many deterministic fast-time wake vortex prediction models
Run deterministic fast-time wake vortex prediction model

Access and process field data

Set-up input for each simulation

1 more deterministic model

Display and Save Results

Model output data files (optional write for documentation)

Model input data files (optional write for documentation)

User request to compare with data

qc check reveals inconsistency with inputs

Wake Research And Prediction System (WRAPS)

Graphical User Interface

Model set-up

Make suggestions

1. APA v3.2
2. APA v3.3
3. APA v3.4
4. D2P v1.0 (NWRA)
5. Linear v1.0
6. STL v3.0
7. STL v4.0
8. STL v5.0
9. STL v6.0
10. STL v7.0
11. TDAWP v1.0
12. TDAWP v2.1
13. TDAWP v2.2
14. VIPER v1.0
15. VIPER v2.0

1 more Monte Carlo simulation
Select Aircraft

Select Weather Profiles

Select Models and Run

Select Aircraft

Select Aircraft Parameters

Select Weather Profiles

Select Models and Run
But what estimates for the uncertainties are appropriate?

<table>
<thead>
<tr>
<th>Aircraft parameters</th>
<th>Environmental parameters</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Time of overflight</td>
<td>1) Air density</td>
<td>1) Parameterizations</td>
</tr>
<tr>
<td>2) Vertical position</td>
<td>2) Ambient turbulence</td>
<td>2) Assumptions</td>
</tr>
<tr>
<td>3) Lateral position</td>
<td>3) Stratification</td>
<td>3) Simplifications</td>
</tr>
<tr>
<td>4) Air speed</td>
<td>4) Crosswind</td>
<td></td>
</tr>
<tr>
<td>5) Weight of aircraft</td>
<td>5) Crosswind shear</td>
<td></td>
</tr>
<tr>
<td>6) Initial vortex separation distance</td>
<td>gradient</td>
<td></td>
</tr>
<tr>
<td>7) Pilot adjustments</td>
<td>6) Headwind</td>
<td></td>
</tr>
</tbody>
</table>

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“Example” Estimates of Uncertainties for B752 That is ~2.2 nm From Threshold

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density at initial height of vortex</td>
<td>1.02 kg/m³</td>
<td>0.02</td>
</tr>
<tr>
<td>Crosswind</td>
<td>-0.6 m/s</td>
<td>2.6</td>
</tr>
<tr>
<td>Headwind</td>
<td>0 m/s</td>
<td>0.44</td>
</tr>
<tr>
<td>EDR</td>
<td>$1 \times 10^{-5}$ m²/s³</td>
<td>Factor of 2</td>
</tr>
<tr>
<td>Potential temperature</td>
<td>300 °K</td>
<td>1</td>
</tr>
<tr>
<td>Potential Temperature Gradient</td>
<td>0 °C/m</td>
<td>0.0025</td>
</tr>
<tr>
<td>Aircraft weight</td>
<td>76340 kg</td>
<td>4400</td>
</tr>
<tr>
<td>Approach speed</td>
<td>64.8 m/s</td>
<td>3.6</td>
</tr>
<tr>
<td>Initial vortex spacing</td>
<td>29.8 m</td>
<td>1</td>
</tr>
<tr>
<td>Initial lateral position</td>
<td>0 m</td>
<td>9</td>
</tr>
<tr>
<td>Initial vertical position</td>
<td>217 m</td>
<td>9</td>
</tr>
</tbody>
</table>
Explanation of Simulation Results With One Model (APA v3.2)

Gray region contains 90% of simulations

Red region contains 50% of simulations

Individual simulations
WRAPS Simulation With One Model (APA v3.2)
WRAPS Simulation With Two Models (APA v3.2 and APA v3.4)
WRAPS Simulation With Three Models (APA v3.2, APA v3.4, TDP v2.1)
Adding Additional Models to Ensemble Tends to Increase Model Spread Slightly and Modifies the Ensemble Mean Only Slightly
A comparable data set of LMCT lidar observations of wake vortex circulation intensity and trajectories is 87 B752 landings at Denver airport in 2003 ($T_{\text{Last}} > 80$ seconds)

Should correspond to low turbulence conditions
87 landings of a B752 at DEN 2003
Overlay of the Model Predictions and Similar Wake Observations
What did we find out?

- Spread between different deterministic models overlaps when small, plausible uncertainties in aircraft and environmental conditions are used.
- Model reproduces observed vortex behavior and predicts approximately the same mean and spread as the observations.
Next Step(s)

- Collect more high quality wake observations, with good weather and aircraft observations
Next Step(s)

- Better estimates of uncertainties (or expected variability) in aircraft and weather inputs

How much do aircraft weights vary? How do the weights vary, is it predictable?

How much variance is there on the aircraft position relative to the glide slope path? How does it vary? Can we use ADS-B to get a better estimate?

What is the relevant timescale to estimate turbulence for aircraft wakes?

What are the errors associated with using weather observations obtained in different locations then where the wake is observed and modeled, and observations obtained at different times or averaged over the wake lifetime?

What are the errors in weather sensing? How do we estimate this?
Next Step(s)

- Model Improvements
  - Wake observation lifetimes
  - High stratification
  - Low turbulence, weak stable stratification


Descent of Wakes modified by stratification

NASA has Funded a New Project

Lack of data was impetus for a new NASA NRA entitled “Wake Vortex Data Collection for Robust Modeling Validation to Enable Advanced, NextGen, Wake-Conscious, Capacity-Enhancing Concepts”
Overview of New NASA NRA (1 of 2)

- Characterize existing sensors and sensing capabilities
- Establish full set of wake vortex, meteorological, aircraft, and air traffic operational parameters required to be measured and test conditions for several test scenarios
- Develop a ground-based, terminal-area, data collection test program to collect data that can be used to validate existing wake vortex prediction tools
Overview of New NASA NRA (2 of 2)

- Collect meteorological and wake vortex position and strength data
- Conduct a robust validation of wake vortex models. Enhance, as required, existing fast-time wake vortex prediction tools using the new data. This includes both deterministic and probabilistic tools that can:
  - Predict the probability of wake location
  - Predict the probability of wake location and strength
Final Questions

- How well do we need to know the weather, and how well can we quantify the uncertainties?
- Can we decrease the probabilistic model uncertainty to a level that is operationally useful? What is that level?
- What is the most critical parameter (or set of parameters) to improve our modeling capabilities? What should the priorities be?