NASA/TM–2014-218152

NASA AVOSS Fast-Time Wake Prediction Models: User’s Guide

Nash'at N. Ahmad and Randal L. VanValkenburg
Langley Research Center, Hampton, Virginia

Matthew Pruis
NorthWest Research Associates, Inc., Redmond, Washington

January 2014

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*
- E-mail your question to help@sti.nasa.gov
- Fax your question to the NASA STI Information Desk at 443-757-5803
- Phone the NASA STI Information Desk at 443-757-5802
- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/TM–2014-218152

NASA AVOSS Fast-Time Wake Prediction Models: User's Guide

Nash'at N. Ahmad and Randal L. VanValkenburg
Langley Research Center, Hampton, Virginia

Matthew Pruis
NorthWest Research Associates, Inc., Redmond, Washington

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

January 2014

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

Contents

List of Acronyms, Abbreviations, and Symbols .... iǿ

Introduction 1

Software Distribution 2

Model Input/Output Filename Convention 3

Model Input File Formats 4

- Case Input File (cases.i) 4
- Aircraft Parameters Input File (YYYY_MO_DY_HRMNSC.ADATA) 4
- Temperature/Theta Profile (YYYY_MO_DY_HRMNSC.TDATA) 5
- Crosswind Profile (YYYY_MO_DY_HRMNSC.UDATA) 6
- Eddy Dissipation Rate Profile (YYYY_MO_DY_HRMNSC.QDATA) 6

Lidar Data File Format 7

- Lidar Data File (YYYY_MO_DY_HRMNSC.cwp) 7

Model Output File Format 8

- Model Output File Format (e.g., YYYY_MO_DY_HRMNSC.apa34) 8
- Model Output File Example (e.g., YYYY_MO_DY_HRMNSC.apa34) 9

Memphis Field Experiment (1995) 10

- Data Processed for Fast-Time Wake Models 10

Evaluation of Fast-Time Models using the Memphis 1995 Data 13

Example from the Memphis 1995 Dataset 15

List of Contributors 17

Acknowledgment 17

References 17

List of Acronyms, Abbreviations, and Symbols

AGL	Above Ground Level
APA	AVOSS Prediction Algorithm
ATM	Air Traffic Management
ATPG	Atmospheric Turbulence Profile Generator
ASOS	Automated Surface Observations System
AVOSS	Aircraft VOrtex Spacing System
AWAS	AVOSS Winds Analysis System
b_0	Initial vortex pair separation (*m*)
B	Wingspan (*m*)
CW	Continuous Wave Lidar
EDR	Eddy Dissipation Rate (m^2/s^3)
ε	Eddy Dissipation Rate (m^2/s^3)
Γ_0	Initial vortex circulation (m^2/s)
IGE	In-Ground Effect
Lidar	LIght Detection And Ranging
MEM	Memphis International Airport, Memphis, Tennessee
NASA	National Aeronautics and Space Administration
NGE	Near-Ground Effect
OGE	Out-of-Ground Effect
PL	Pulsed Lidar
ρ	Air density (kg/m^3)
RASS	Radio Acoustic Sounding System
SAO	Surface Aerodrome Observations
θ	Potential Temperature/Theta (K)
TASS	Terminal Area Simulation System
TDAWP	TASS Driven Algorithms for Wake Prediction
TDP	Abbreviation used for the TDAWP model
U	Airspeed (m/s)
V_0	Initial vortex pair descent velocity (m/s)
W	Landing weight of the aircraft (*kg*)
y_0	Initial position of the vortex pair with respect to the runway centerline (*m*)
z_0	Initial vortex height AGL (*m*)

Introduction

The National Aeronautics and Space Administration (NASA) is developing fast-time wake transport and decay models to safely enhance the capacity of the National Airspace System (NAS). These models are empirical algorithms used for real-time predictions of wake transport and decay based on aircraft parameters and ambient weather conditions. The aircraft dependent parameters include the initial vortex descent velocity (V_0) and the vortex pair separation distance (b_0). The atmospheric initial conditions include vertical profiles of temperature or potential temperature (θ), eddy dissipation rate (EDR), and crosswind. The model output consists of time history of vortex circulation strength and position. The fast-time wake models can be used for the systems level design of advanced air traffic management (ATM) concepts that safely increase the capacity of the NAS. It is also envisioned that at some later stage of maturity, these models could be used operationally, not only within the terminal airspace but also as onboard tools to support concepts such as dynamic separation of aircraft.

NASA's first fast-time wake transport and decay model was developed by Greene (1986). In the late 1990s, under NASA's Aircraft Vortex Spacing System (AVOSS) project, significant advances were made in wake vortex modeling based on the data from field experiments and large eddy simulations. The initial versions of the AVOSS Wake Vortex Prediction Algorithm (APA) were developed during the AVOSS program and demonstrated in the AVOSS demo at the Dallas/Ft. Worth (Hinton 2001). The APA model computes the out-of-ground-effect (OGE) decay and descent based on Sarpkaya (Sarpkaya 2000; Sarpkaya et al. 2001). The model has an algorithm for enhanced rate of decay during the ground effect developed by Proctor et al. (2000). The scheme to compute lateral vortex transport is based on the vertical profile of crosswind (Robins and Delisi 2002), and the in-ground-effect (IGE) transport accounts for vortex spreading and rebound (Robins et al. 2002). The code development of APA is described in Robins and Delisi (2002).

NASA has also developed the TASS (Terminal Area Simulation System) Derived Algorithms for Wake Prediction (TDAWP) model. In the TDAWP model, the Sarpkaya component is replaced with algorithms developed from parametric studies using a Large Eddy Simulation (LES) model. The TDAWP model is described in Proctor et al. (2006) and Proctor and Hamilton (2009). The current version of the TDAWP model includes the effect of the crosswind shear gradient on transport. The TDAWP model is also denoted by TDP.

The current distribution includes the latest versions of the APA (3.4) and the TDP (2.1) models. This User's Guide provides detailed information on the model inputs, file formats, and the model output. An example of a model run is also provided. A brief description of the Memphis 1995 Wake Vortex Dataset is also provided. Additional questions regarding this software distribution can be directed to Nashat Ahmad (nashat.n.ahmad@nasa.gov) or Randy VanValkenburg (randal.l.vanvalkenburg@nasa.gov).

Software Distribution

NASA's AVOSS Fast-Time Wake Prediction software distribution is given below:

```
avoss/
|
`--bin/
|   |
|   +-- apa34.exe
|   |
|   `-- tdp21.exe
|
`--doc/
|   `-- APA-UsersGuide.pdf
|
`--etc/
|   `-- cases.i
|
`--mem/                  Memphis 1995 Wake Vortex Dataset
|   |
|   +-- ADATA/           aircraft information and initial vortex location
|   |
|   +-- QDATA/           vertical profiles of eddy dissipation rate
|   |
|   +-- TDATA/           vertical profiles of potential temperature
|   |
|   +-- UDATA/           vertical profiles of crosswinds
|   |
|   +-- UPROXY/          vertical profiles of proxy crosswinds
|   |
|   +-- CWP/             lidar data for port vortex
|   |
|   `-- CWS/             lidar data for starboard vortex
|
`--run/
    |
    +-- cases.i                      list of cases to run
    |
    +-- 1995-08-10-230029.apa34      APA3.4 output
    |
    +-- 1995-08-10-230029.tdp21      TDP2.1 output
    |
    +-- 1995-08-10-230029.tplt       Potential Temperature(θ) input
    |
    +-- 1995-08-10-230029.qplt       Eddy Dissipation Rate(ε) input
    |
    `-- 1995-08-10-230029.uplt       Crosswinds input
```

Model Input/Output Filename Convention

The file names are chosen to give a unique identifier for each case and model run. The unique identifier has the form:

YYYY_MO_DY_HRMNSC

where,

YYYY	=	Four digit year
MO	=	Two digit month
DY	=	Two digit day
HRMNSC	=	Six digit HourMinuteSeconds

Example:

2003_09_19_181019 has the following associated input files:

2003_09_19_181019.ADATA	Initial Vortex Location & Aircraft Parameters
2003_09_19_181019.TDATA	Vertical Profile of Temperature or Theta
2003_09_19_181019.UDATA	Vertical Profile of Crosswind
2003_09_19_181019.QDATA	Vertical Profile of Eddy Dissipation Rate

The model output is written to (depending on the model used):

2003_09_19_181019.apa34	APA3.4 output
2003_09_19_181019.tdp21	TDP2.1 output

Model Input File Formats

Case Input File (cases.i)

The first six lines list the paths to input files. Line number 7 has the total number of cases (maximum number of cases = 5000) in the file and the type of lidar. The lidar type is not used in fast-time models – it is used by plotting and validation routines. The rest of the file lists the unique identifiers for each case. The path names should have a maximum length of 132 characters.

CASE FILE (cases.i)

```
/home/nnahmad/apa-models/data/MEM1995/ADATA/
/home/nnahmad/apa-models/data/MEM1995/QDATA/
/home/nnahmad/apa-models/data/MEM1995/TDATA/
/home/nnahmad/apa-models/data/MEM1995/UDATA/
/home/nnahmad/apa-models/data/MEM1995/CWP/
/home/nnahmad/apa-models/data/MEM1995/CWS/
2    0     !  total number of cases to run/lidar type
1995-08-06-230412
1995-08-06-232159
```

Aircraft Parameters Input File (YYYY_MO_DY_HRMNSC.ADATA)

The first 11 lines of this file contain the header information. After the header lines, the file contains the initial vortex location and the aircraft data: Initial lateral location of the vortex (y_0), initial height of the vortex (z_0), initial descent velocity (V_0), and the separation distance (b_0) of the vortex pair. The units are MKS.

AIRCRAFT PARAMETERS FILE (YYYY_MO_DY_HRMNSC.ADATA)

```
# Location: MEM, 18L_TANG
# Run Number: 1026
# A/C Type: AT43
# Wing span* (m): 24.6
# Weight* (kg): 13940
# ACspeed* (m/s): 63.4
# Air Density* (kg/m3): 1.2
# This file was created on 22-Mar-2012 12:42:37 Pacific Time
# File created by Matt Pruis, NWRA, matt@nwra.com
# *If data not provided with original data set, then default values used.
# Data File Format: yo (m),zo (m),Vo (m/s), bo (m)
5.2895, 90.03, 0.76635, 19.321
```

Temperature/Theta Profile (YYYY_MO_DY_HRMNSC.TDATA)

The first 11 lines in this file contain header information. The first line after the header information gives the total number of data points in the file. If negative, then the file contains potential temperatures, otherwise the data are temperatures. The rest of the file has two columns: the first column lists the AGL height in meters and the second column lists the potential temperature in K or temperature in °C. If the user inputs a temperature profile, then it is converted by the model to potential temperature (θ).

At least three data points are required in the initial profile and the points should extend above and below the heights of vortex descent trajectory. If the input potential temperature profile contains regions of unstable stratification, then those values are set to zero (neutral stratification) within both the APA and TDP codes. Observations from various field sensors as well as simulation data from mesoscale models (Ahmad et al. 2013) can be used to generate the vertical temperature/potential temperature profiles. It should be noted that the fast-time wake models use potential temperature in model calculations.

TEMPERATURE PROFILE DATA (YYYY_MO_DY_HRMNSC.TDATA)

```
# Location: MEM, 18L_TANG
# Run Number: 1026
# A/C Type: AT43
# Potential modifications from original data include:
# (1) extrapolation above and below profile (with N=0 in these regions)
# (2) removal of unstable regions that are not attached to ground
#     (with N=0 in these regions)
# This file was created on 22-Mar-2012 12:42:37 Pacific Time
# File created by Matt Pruis, NWRA, matt@nwra.com
# Data File Format (1st line): number of points (-ve indicates theta)
# Data File Format (remainder of file): z (m)  potential temperature (K)
-120
0, 303.98
5, 303.98
10, 304.04       and so on.....
```

Crosswind Profile (YYYY_MO_DY_HRMNSC.UDATA)

Similar in format to the **xxx.TDATA** file, but contains crosswinds (*m*/*s*). Heights are in meters. Crosswind profiles can be generated from the lidar data or estimated from the wake vortex trajectory (Pruis et al. 2011).

CROSSWIND PROFILE DATA (YYYY_MO_DY_HRMNSC.UDATA)

```
# Location: MEM, 18L_TANG
# Run Number: 1026
# A/C Type: AT43
# Potential modifications from original data include:
# (1) extrapolation above and below profile (with U constant in these regions)
# This file was created on 22-Mar-2012 12:42:37 Pacific Time
# File created by Matt Pruis, NWRA, matt@nwra.com
# Data File Format (1st line): number of data points
# Data File Format (remainder of file): z (m)  Crosswind (m/s)
120
0, 2.124
10, 2.074       and so on.....
```

Eddy Dissipation Rate Profile (YYYY_MO_DY_HRMNSC.QDATA)

Similar in format to the **xxx.TDATA** file, but contains the eddy dissipation rates (m^2/s^3). Heights are in meters. Given two observations of EDR, the vertical EDR profile can be generated using atmospheric boundary layer similarity theory (Han et al. 2000). EDR profiles can also be estimated from lidar data (Pruis et al. 2013). Input EDR values less than $10^{-7} m^2/s^3$ are set to $10^{-7} m^2/s^3$ within the models.

EDDY DISSIPATION RATE DATA (YYYY_MO_DY_HRMNSC.QDATA)

```
# Location: MEM, 18L_TANG
# Run Number: 1026
# A/C Type: AT43
# Potential modifications from original data include:
# (1) extrapolation above and below profile (with EDR constant in these regions)
# This file was created on 22-Mar-2012 12:42:37 Pacific Time
# File created by Matt Pruis, NWRA, matt@nwra.com
# Data File Format (1st line): number of data points
# Data File Format (remainder of file): z (m)  EDR (m2/s3)
120
0, 0.0026156
5, 0.0026156
15, 0.002405
20, 0.0023001
30, 0.0020895    and so on.....
```

Lidar Data File Format

Lidar Data File (YYYY_MO_DY_HRMNSC.cwp)

For each case there are two lidar data files: one each for the port and the starboard vortices. The filename conventions are as follows:

2003_09_19_181019.cwp	Continuous Wave Lidar Port Vortex Data
2003_09_19_181019.cws	Continuous Wave Lidar Starboard Vortex Data
2003_09_19_181019.plp	Pulsed Lidar Port Vortex Data
2003_09_19_181019.pls	Pulsed Lidar Starboard Vortex Data

In most of the field experiments only one type of lidar was used and therefore a particular dataset will have either CW or PL files. In the Denver 2003 Field Experiment (Dougherty et al. 2004) both CW and PL lidars were deployed.

The first six lines in the lidar data files contain the header information. Missing data points in the files are marked by a **-9999**. Please note that it is not uncommon for the lidar files to contain points that include valid times and vortex positions, but for which the circulation cannot be calculated due to missing or invalid data values. Consequently for a given vortex, the plots of circulation may display fewer discrete points than do the corresponding plots of lateral transport or altitude.

LIDAR DATA FILE (YYYY_MO_DY_HRMNSC.cwp)

```
# Location: MEM, 18L_TANG
# Run Number: 1026
# A/C Type: AT43
# This file was created on 22-Mar-2012 12:42:38 Pacific Time
# File created by Matt Pruis, NWRA, matt@nwra.com
# Data File Format: time_p(s), y_pos_p(m), z_pos_p(m), Circ_p(m2/s)
21
8.88, 5, 87, 125.9091
11.4, 8.3, 84.7, 158.1455
13.6, 18.4, 92.5, -9999
15.57, 20.5, 83.2, 123.7773   and so on.....
```

Model Output File Format

Model Output File Format (e.g., YYYY_MO_DY_HRMNSC.apa34)

The model output files are currently written in **Tecplot®** format. The model output file gives the time history of position (lateral distance and altitude) and circulation strength of both the port and starboard vortices. The output variables are listed in Table 1.

Table 1: Fast-Time Wake Model Output

column #	variable	description
1	time	Time (seconds)
2	yp	Lateral position of port vortex (m)
3	zp	Altitude of port vortex (m)
4	gp	Circulation of port vortex (m^2/s)
5	ys	Lateral position of starboard vortex (m)
6	zs	Altitude of starboard vortex (m)
7	gs	Circulation of starboard vortex (m^2/s)

The output filename extension is based on the model type:

2003_09_19_181019.apa34 APA3.4 output

2003_09_19_181019.tdp21 TDP2.1 output

In addition to the model output, for each run the environmental initial conditions are also written to files for plotting purposes:

2003_09_19_181019.uplt Crosswinds

2003_09_19_181019.qplt EDR

2003_09_19_181019.tplt Theta/Temperature

Model Output File Example (e.g., YYYY_MO_DY_HRMNSC.apa34)

An example of a model output file is shown below:

MODEL OUTPUT (YYYY_MO_DY_HRMNSC.apa34)

```
TITLE="APA 3.4"
VARIABLES = "Time(s)", "Yp(m)", "Zp(m)", "Gp(m^2/s)", "Ys(m)", "Zs(m)", "Gs(m^2/s)"
ZONE T="31", I= 1097
   0.000     8.356    41.821    63.793    25.164    41.821    63.793
   0.100     8.300    41.761    63.738    25.108    41.761    63.738
   0.200     8.243    41.700    63.683    25.051    41.700    63.683
   0.300     8.187    41.640    63.627    24.995    41.640    63.627
   0.400     8.130    41.580    63.572    24.938    41.580    63.572
   0.500     8.074    41.520    63.517    24.882    41.520    63.517
   0.600     8.017    41.460    63.461    24.825    41.460    63.461
   0.700     7.960    41.399    63.406    24.768    41.399    63.406
   0.800     7.904    41.339    63.351    24.712    41.339    63.351
   0.900     7.847    41.279    63.296    24.655    41.279    63.296
   1.000     7.790    41.220    63.241    24.598    41.220    63.241
   1.100     7.734    41.160    63.186    24.542    41.160    63.186
   1.200     7.677    41.100    63.131    24.485    41.100    63.131
   1.300     7.620    41.040    63.076    24.428    41.040    63.076
   1.400     7.563    40.980    63.021    24.371    40.980    63.021
   1.500     7.507    40.921    62.966    24.315    40.921    62.966
   1.600     7.450    40.861    62.912    24.258    40.861    62.912
   1.700     7.393    40.802    62.857    24.201    40.802    62.857
   1.800     7.336    40.742    62.802    24.144    40.742    62.802
   1.900     7.279    40.683    62.748    24.087    40.683    62.748
   2.000     7.222    40.623    62.693    24.030    40.623    62.693
   and so on.....
```

Memphis Field Experiment (1995)

A comprehensive field experiment to measure wake vortices and the associated ambient meteorological conditions was conducted at the Memphis International Airport in Memphis, Tennessee from August 6 through August 29, 1995 (Zak 1995; Campbell, et al. 1997). The experiment was sponsored under NASA Langley Research Center's Aircraft Vortex Spacing System (AVOSS) project (Hinton 1995; Perry et al. 1997). The wake data were collected using a continuous wave lidar (Figure 1). The meteorological sensors included radiosondes, sodars, a wind profiler, one 150*ft* high meteorological tower, a Radio Acoustic Sounding System (RASS), and NASA Langley's OV-10 research aircraft. The radiosondes were used to measure winds and temperature measurements (10*s* averages) at 50*m* vertical resolution. The OV-10 aircraft was flown at selected times and took measurements of temperature and winds at a sample rate of 10*Hz*. Temperature (5*min* averages) was measured using RASS every 30*min* at 14 vertical levels from 127*m* to 1492*m*. The 150*ft* (45.7*m*) meteorological tower was equipped with a large array of sensor systems. Winds, temperature and moisture were measured from the tower at 5*m*, 10*m*, 20*m*, 30*m,* and 42*m* heights. Turbulence quantities (turbulence kinetic energy and eddy dissipation rate) were estimated from wind measurements at 5*m* and 40*m* heights. Rain rate, soil temperature, soil moisture, barometric pressure, and incoming and outgoing solar radiation also were measured by the sensors deployed on the meteorological tower. Standard meteorological data such as atmospheric pressure, temperature, moisture, cloud cover, visibility, etc. were obtained from the National Weather Service's Surface Aerodrome Observations (SAO) and the Automated Surface Observations System (ASOS).

Data Processed for Fast-Time Wake Models

Aircraft Data

The aircraft data used by the fast-time wake prediction models include the initial position (offset) of the vortex pair with respect to the runway centerline (y_0), the initial height of the vortices (z_0), the initial vortex descent rate (V_0) and the initial separation of vortices (b_0).

The initial position (offset) of the vortex pair with respect to the runway centerline y_0 was estimated using an average of the first few data points for each landing. The initial height of the vortices z_0 was estimated from backward extrapolation of the altitude trajectory in time. The initial separation distance between the vortices b_0 was estimated assuming an elliptical wing loading,

$$b_0 = \frac{\pi}{4} B \tag{1}$$

where B is the wingspan of the aircraft. The initial vortex descent rate was estimated from the aircraft weight, aircraft speed, air density, and the initial vortex separation b_0,

$$V_0 = \frac{gW}{2\pi\rho U b_0^2} \tag{2}$$

where g (=9.81m/s^2) is the acceleration due to gravity, ρ is the air density - which was assumed to be 1.2kg/m^3 for all the landings, U is the reported airspeed, and W is the reported landing weight of the aircraft.

Types of aircraft observed at different measurement sites are listed in Table 2 and a graphical presentation of aircraft distribution is shown in Figures 1-2. The Armory site was located south of the airport, while the TANG, Tchulahoma, and Threshold sites were all located at the north end of the airport.

Crosswinds and Headwinds

The profiles of the mean crosswind and headwind were generated by the AVOSS Winds Analysis System (AWAS) using an optimal estimation of data fusion from several different wind sensors including two Doppler radars, the meteorological tower, and the SODAR. There are some known deficiencies in the AWAS profiles which are discussed in detail by Dasey et al. (1998). In the current distribution, only the crosswinds are included.

Eddy Dissipation Rate

EDR profiles were estimated using the two sonic anemometers on the meteorological tower and extrapolating to heights using atmospheric boundary layer similarity theory (Han et al. 2000). The profiles were generated using the atmospheric turbulence profile generator (ATPG) code which implements the algorithms described in Han et al. (2000). Turbulence profiles were extrapolated to the ground ($z = 0$) and to a height above the observed vortices with a constant EDR value whenever the measured profiles did not extend to those heights.

Stratification

Temperature profiles were estimated using a fusion of the RASS and temperature sensors on the ASOS and the meteorological tower. The temperature profiles were converted to potential temperatures using the dry adiabatic lapse rate. The highest temperature measurement on the tower was at approximately 43*m* AGL and the lowest observation of the RASS was at 127*m*. A known deficiency in the profiles is a frequent mismatch in these two temperatures, leading to unrealistic gradients in the temperature profile within this region. This can sometimes lead to highly unstable persistent regions that are not attached to the ground. The potential temperature profiles were therefore pre-processed to remove these unstable regions by making the potential temperature constant in these regions.

Table 2: Aircraft Observed at different Measurement Sites

Aircraft Type	Armory	TANG	Tchulahoma	Threshold	Total
AT42	1	1	-	-	2
B727	86	1	3	24	114
B737	3	-	-	-	3
B757	5	2	1	-	8
BA31	-	-	2	-	2
DC10	25	-	-	2	27
DC9	57	19	6	3	85
EA30	11	-	-	-	11
EA31	9	-	-	1	10
EA32	15	7	2	1	25
FK10	5	2	-	-	7
MD11	-	-	-	1	1
SF34	2	-	8	-	10
Total	**219**	**32**	**22**	**32**	**305**

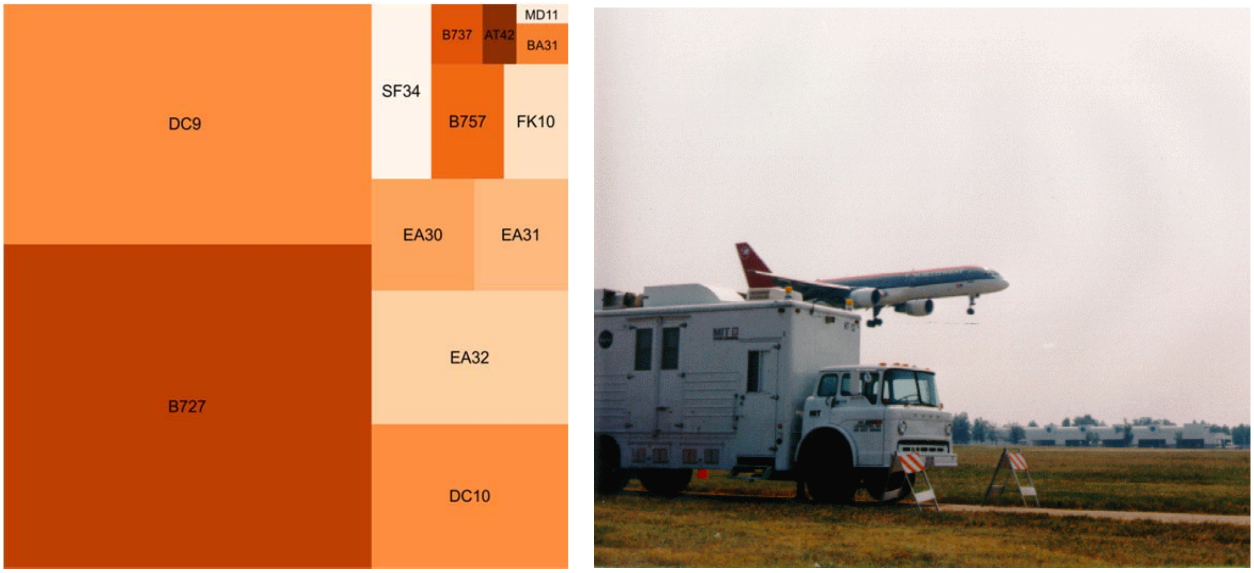


Figure 1: Distribution of the aircraft types in the MEM dataset is shown in the left panel. A B757 landing in the background of the NASA lidar van is shown in the right panel.

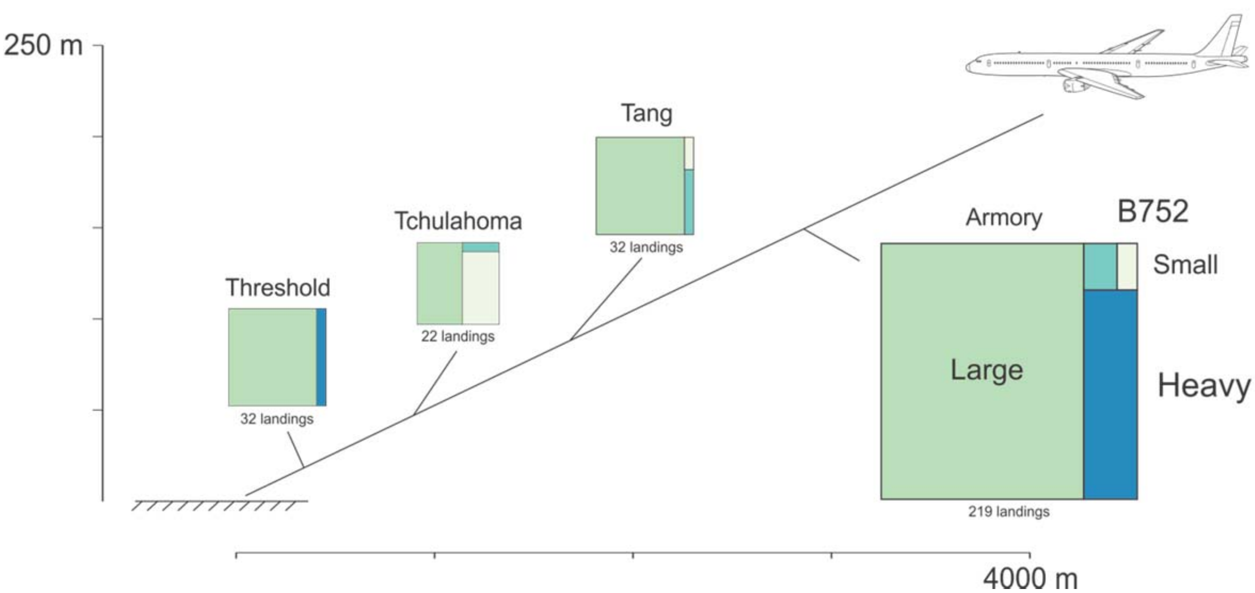


Figure 2: Distribution of the lidar data by aircraft category and location. The Armory site was located south of the airport, while the TANG, Tchulahoma, and Threshold sites were all located at the north end of the airport.

Evaluation of Fast-Time Models using the Memphis 1995 Data

Several evaluations of NASA's fast-time models have been conducted in the past (Proctor and Hamilton 2009; Pruis and Delisi 2011a; Feigh et al. 2012). Under a NASA Research Announcement (Enabling Super-Dense Operations by Advancing the State of the Art of Fast-Time Wake Vortex Modeling), the NorthWest Research Associates (NWRA) was tasked to conduct an independent evaluation of NASA's fast-time models over a three year period. This evaluation concluded that in general the errors in model circulation predictions had a mean root mean square error on the order of $0.2\Gamma_0$ to $0.3\Gamma_0$ (Γ_0 is the initial wake circulation), the vertical transport errors were on the order of $0.5b_0$ and the lateral transport errors were on the order of b_0 (Pruis and Delisi 2011b). NWRA also demonstrated that the lateral transport errors can be reduced to as low as $0.5b_0$ if more accurate crosswind initial conditions (e.g., by using proxy crosswinds as initial conditions) were provided to the fast-time models (Pruis et al. 2011).

In this section the current distribution of the fast-time models are evaluated using the continuous wave lidar observations from the Memphis 1995 field experiment. The accuracy of predictions for the two models was quantified in terms of *root mean square error* ($Error_{rms}$), *mean absolute error* ($Error_{mae}$), and *Bias*:

$$Error_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i^{apa} - x_i^{obs}\right)^2}\ ; \quad Error_{mae} = \frac{1}{n}\sum_{i=1}^{n}\left|x_i^{apa} - x_i^{obs}\right|; \quad Bias = \frac{1}{n}\sum_{i=1}^{n}\left(x_i^{apa} - x_i^{obs}\right) \tag{3}$$

The prediction errors in TDP2.1, and APA3.4 for all Memphis cases are given in Table 3. The errors in TDP2.1 and APA3.4 categorized approximately by phase (OGE, NGE, and IGE) are given in Tables 4-6. Proxy crosswinds were not used in this evaluation.

For the Memphis data, the groupings of the landings were based on the measurement site where the observations were obtained. The OGE observations are the measurements obtained at the 36R_Armory site, where the mean initial vortex height was 180*m*. The NGE observations were obtained from the 18L_TANG site where the mean initial observations, were at a height of 99*m*. The IGE data came from two different lidar locations; the 27_Tchulahoma and the 27_Threshold data. The mean height of the initial vortex observation for these two sites was 36*m*. In dimensional space, the combined different phases of vortex trajectory (OGE, NGE and IGE) are defined as follows:

$$\begin{aligned} z_o &\geq 130m && \Rightarrow \text{OGE} \\ 75m \leq z_o &< 130m && \Rightarrow \text{NGE} \\ z_o &< 75m && \Rightarrow \text{IGE} \end{aligned} \tag{4}$$

Table 3: Memphis: All 305 Cases

Model	Circulation (normalized by Γ_0)			Lateral Transport (normalized by b_0)			Altitude (normalized by b_0)		
	rmse	mae	bias	rmse	mae	bias	rmse	mae	bias
TDP2.1	0.26	0.22	0.02	1.01	0.83	0.09	0.52	0.44	0.07
APA3.4	0.24	0.21	-0.05	0.97	0.80	0.10	0.54	0.46	0.14

Table 4: Memphis OGE: 219 Cases

Model	Circulation (normalized by Γ_0)			Lateral Transport (normalized by b_0)			Altitude (normalized by b_0)		
	rmse	mae	bias	rmse	mae	bias	rmse	mae	bias
TDP2.1	0.25	0.21	0.03	1.06	0.87	0.16	0.58	0.50	0.06
APA3.4	0.23	0.20	-0.04	1.02	0.83	0.18	0.60	0.51	0.15

Table 5: Memphis (NGE): 32 Cases

Model	Circulation (normalized by Γ_0)			Lateral Transport (normalized by b_0)			Altitude (normalized by b_0)		
	rmse	mae	bias	rmse	mae	bias	rmse	mae	bias
TDP2.1	0.25	0.21	-0.02	1.05	0.86	-0.32	0.46	0.39	0.12
APA3.4	0.25	0.21	-0.12	1.04	0.86	-0.33	0.47	0.39	0.18

Table 6: Memphis (IGE): 54 Cases

Model	Circulation (normalized by Γ_0)			Lateral Transport (normalized by b_0)			Altitude (normalized by b_0)		
	rmse	mae	bias	rmse	mae	bias	rmse	mae	bias
TDP2.1	0.31	0.26	0.02	0.67	0.58	0.02	0.23	0.20	0.06
APA3.4	0.31	0.26	-0.05	0.67	0.57	0.01	0.22	0.20	0.02

Example from the Memphis 1995 Dataset

An example case is given in the **run/** directory of the distribution. The directory, contains the following **cases.i** file:

cases.i
/home/nnahmad/apa-models/avoss/mem/ADATA/ **/home/nnahmad/apa-models/avoss/mem/QDATA/** **/home/nnahmad/apa-models/avoss/mem/TDATA/** **/home/nnahmad/apa-models/avoss/mem/UPROXY/** **/home/nnahmad/apa-models/avoss/mem/CWP/** **/home/nnahmad/apa-models/avoss/mem/CWS/** **1 0** **1995-08-10-230029**

The user needs to edit the first six lines to reflect the location of the input files. In this case, the proxy crosswinds were used. The number of cases is **1** and the lidar flag is set to **0** for the CW lidar. *The lidar flag is not used by the fast-time models and is used only by post-processing routines*. After editing the **cases.i** file, the fast-time models **tdp21.exe** and, **apa34.exe** can be invoked. Figure 3 shows the environmental initial conditions as well as the ***.ADATA** file for this case. The output of APA3.4 and TDP2.1 is compared with the CW lidar data in Figures 4-5.

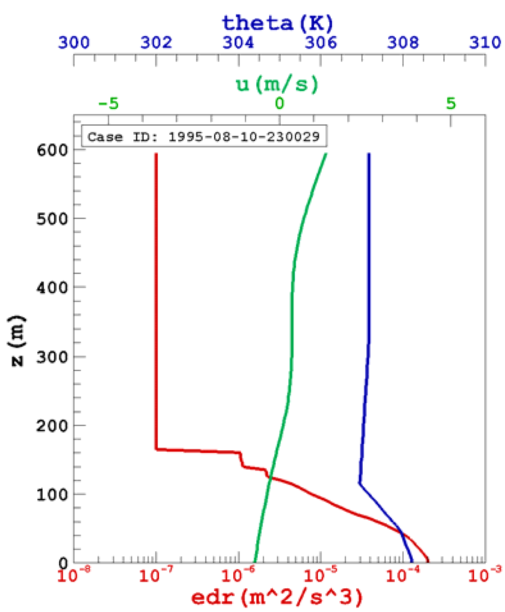
Environmental Initial Conditions	ADATA File
	**# Location: MEM, 36R_Armory** **# Run Number: 1108** **# A/C Type: DC93** **# Wing span* (m): 28.5** **# Weight* (kg): 46653** **# ACspeed* (m/s): 78.1** **# Air Density* (kg/m3): 1.2** **# File was created on 22-Mar-2012** **# File created by Matt Pruis, NWRA** **#** **# yo (m),zo (m),Vo (m/s), bo (m)** **17.301, 218.589, 1.5512, 22.384**

Figure 3: The environmental initial conditions (crosswind, eddy dissipation rate, and potential temperature are plotted in the left panel. The ADATA file for this example case is given in the right panel.

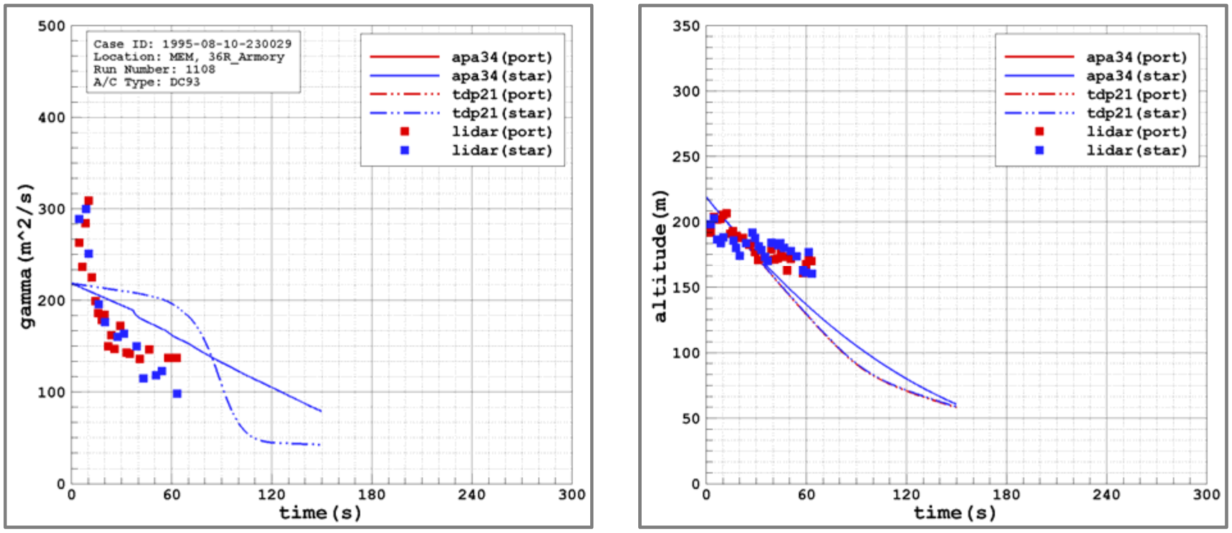


Figure 4: The circulation strength (m^2/s) predicted by APA3.4 and TDP2.1 are plotted along with the lidar data in the left panel. The right panel shows the comparison of vortex descent with lidar observations.

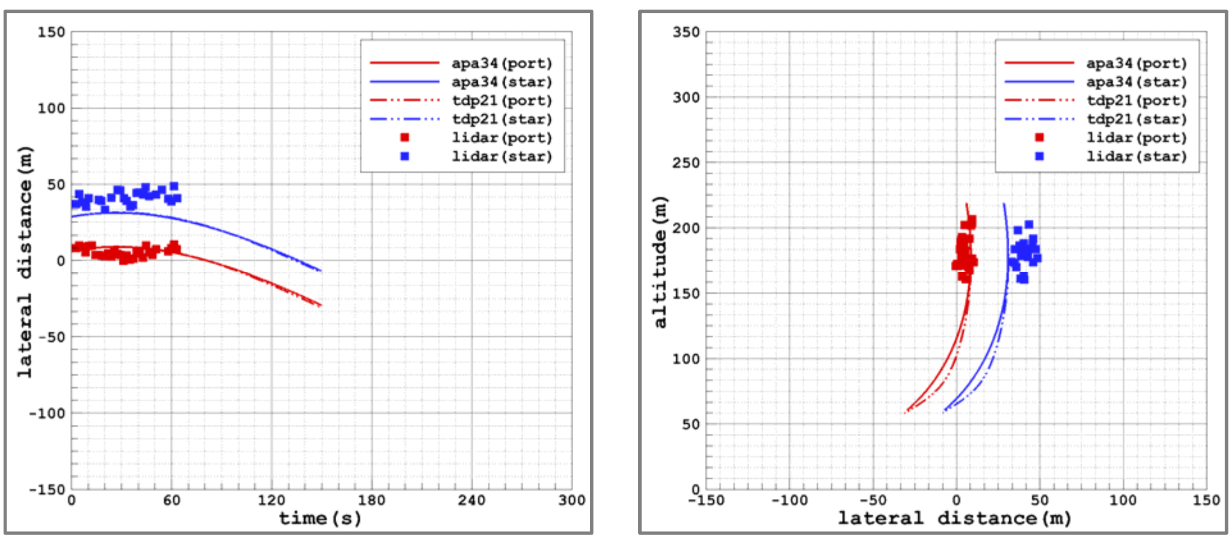


Figure 5: The vortex trajectories predicted by APA3.4 and TDP2.1 are plotted along with the lidar data.

List of Contributors

The following individuals (listed in alphabetical order) have contributed in the development and or evaluation of one or more components of the NASA AVOSS Fast-Time Wake Models:

- Ahmad, N.N. (NASA Langley)
- Bagwell, D.R. (NASA Langley)
- Delisi, D.P. (NorthWest Research Associates)
- Greene, G.C. (NASA Langley/FAA)
- Hamilton, D.W. (NASA Langley)
- Hinton, D.A. (NASA Langley)
- Johnson, E.J. (NASA Langley)
- Lai, D.Y. (NorthWest Research Associates)
- Proctor, F.H. (NASA Langley)
- Pruis, M.J. (NorthWest Research Associates)
- Robins, R.E. (NorthWest Research Associates)
- Rutishauser , D.K. (NASA Langley)
- Sarpkaya, T. (Naval Postgraduate School)
- Switzer, G.F. (Analytical Services and Materials)
- VanValkenburg, R.L. (NASA Langley)

Acknowledgment

Many thanks to Fred Proctor and Neil O'Connor for reviewing this document and for their helpful comments and suggestions.

References

Ahmad, N.N., F.H. Proctor, R.L. VanValkenburg, M.J. Pruis, F. Limon Duparcmeur, "Mesoscale Simulation Data for Initializing Fast-Time Wake Transport and Decay Models," AIAA Paper 2013-0429.

Campbell, S.D., et al., "Wake Vortex Field Measurement Program at Memphis, TN Data Guide", Lincoln Laboratory, Massachusetts Institute of Technology. Project Report NASA/L-2. 1997.

Dasey, T.J., R.E. Cole, R.M. Heinrichs, M.P. Matthew, and G.H. Perras, "Aircraft Vortex Spacing System (AVOSS) Initial 1997 System Deployment at Dallas/Ft. Worth (DFW) Airport," Lincoln Laboratory, Massachusetts Institute of Technology, Project Report NASA/L-3, 1998.

Dougherty, R.P., F.Y. Wang, E.R. Booth, M.E. Watts, N. Fenichel, R.E. D'Errico, "Aircraft Wake Vortex Measurements at Denver International Airport," AIAA Paper 2004-2880.

Feigh, K.M., L. Sankar, V. Manivannan, “Statistical Determination of Vertical Resolution Requirements for Real-Time Wake-Vortex Prediction”, *Journal of Aircraft*, Vol. 49, 2012, pp. 822-835.

Green, G.C., “An Approximate Model of Vortex Decay in the Atmosphere”, *Journal of Aircraft*, Vol. 23, 1986, pp. 566-573.

Hinton, D.A., “Aircraft Vortex Spacing System (AVOSS) Conceptual Design”, NASA-TM-110184, 1995.

Hinton, D.A., “Description of Selected Algorithms and Implementation Details of a Concept-Demonstration Aircraft Vortex Spacing System (AVOSS),” NASA TM-2001-211027.

Han, J., S.P. Arya, S. Shen, Y. Lin, “An Estimation of Turbulent Kinetic Energy and Energy Dissipation Rate Based on Atmospheric Boundary Layer Similarity Theory”, NASA-CR-2000-210298. 2000.

Perry, R.B., D.A. Hinton, and R.A. Stuever, “NASA Wake Vortex Research for Aircraft Spacing,” AIAA Paper 1997-0057.

Proctor, F.H., Hamilton, D.W. and Han, J., “Wake Vortex Transport and Decay in Ground Effect: Vortex Linking with the Ground,” AIAA-2000-0757.

Proctor, F.H., D.W. Hamilton, G.F. Switzer, “TASS Driven Algorithms for Wake Prediction,” AIAA Paper 2006-1073.

Proctor, F.H., “Evaluation of Fast-Time Wake Vortex Prediction Models,” AIAA Paper 2009-0344.

Pruis, M.J., D.P. Delisi, N.N. Ahmad, F.H. Proctor, “Atmospheric Turbulence Estimates from a Pulsed Lidar,” AIAA Paper 2013-0512.

Pruis, M.J., D.P. Delisi, N.N. Ahmad, “Comparisons of Crosswind Velocity Profile Estimates Used in Fast-Time Wake Vortex Prediction Models,” AIAA Paper 2011-1002.

Pruis, M.J., D.P. Delisi, “Assessment of Fast-Time Wake Vortex Prediction Models using Pulsed and Continuous Wave Lidar Observations at Several Different Airports,” 2011a, AIAA Paper 2011-3035.

Pruis, M.J., D.P. Delisi, “Assessment of the Capabilities of Six Deterministic Fast-time Wake Vortex Prediction Models,” NorthWest Research Associates Report NWRA-12-RS443.

Robins, R.E., and D.P. Delisi, “NWRA AVOSS Wake Vortex Prediction Algorithm Version 3.1.1,” NASA CR 2002-211746.

Robins, R.E., Delisi, D.P., and Greene, G.C., “Algorithm for Prediction of Trailing Vortex Evolution,” *Journal of Aircraft*, Vol. 38, 2001, pp. 911-917.

Sarpkaya, T., “New Model for Vortex Decay in the Atmosphere,” *Journal of Aircraft*, Vol. 37, 2000, pp. 53-61.

Sarpkaya, T., R.E. Robins, and D.P. Delisi, “Wake-Vortex Eddy-Dissipation Model Predictions Compared with Observations,” *Journal of Aircraft*, Vol. 38, 2001, pp. 687- 692.

Zak, J.A., "Cases of Interesting Meteorological Conditions during Wake Vortex Measurements at Memphis, Tennessee during August 1995", Vigyan Interim Report for NASA Contract NAS1-19341. 1996.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01- 01 - 2014	Technical Memorandum	

4. TITLE AND SUBTITLE

NASA AVOSS Fast-Time Wake Prediction Models: User's Guide

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Ahmad, Nash'at N.; VanValkenburg, Randal L.; Pruis, Matthew

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

411931.02.01.07.13.07

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

L-20353

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)

NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

NASA/TM-2014-218152

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 01
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The National Aeronautics and Space Administration (NASA) is developing and testing fast-time wake transport and decay models to safely enhance the capacity of the National Airspace System (NAS). The fast-time wake models are empirical algorithms used for real-time predictions of wake transport and decay based on aircraft parameters and ambient weather conditions. The aircraft dependent parameters include the initial vortex descent velocity and the vortex pair separation distance. The atmospheric initial conditions include vertical profiles of temperature or potential temperature, eddy dissipation rate, and crosswind. The current distribution includes the latest versions of the APA (3.4) and the TDP (2.1) models.
This User's Guide provides detailed information on the model inputs, file formats, and the model output. An example of a model run and a brief description of the Memphis 1995 Wake Vortex Dataset is also provided.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	26	(443) 757-5802