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Evaluation, Analysis and Results of the DANTi Flight Test Data, the DAIDALUS Detect and Avoid Algorithm, and the DANTi Concept for Detect and Avoid in the Cockpit

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August 2020

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Abstract

The DAIDALUS Detect and Avoid Algorithm [1] was developed to address the operational needs of Unmanned Aerial Systems (UAS) and meet the Minimum Operational Performance Standards for Detect and Avoid [2]. The DANTi (Detect and Avoid iN the cockpit) concept [3], developed at the National Aeronautics and Space Administration (NASA) Langley Research Center, leverages advancements achieved in surveillance and Detect and Avoid technologies for unmanned aircraft systems as a safety enhancing capability for pilots of manned aircraft.

Pilots operating under Visual Flight Rules and not receiving Air Traffic Control radar services rely on see and avoid to remain well clear of other aircraft and avoid collisions. The DANTi concept has been conceived as a safety enhancement capability to remain well clear and avoid potential collisions. The DANTi concept uses a traffic display to provide situational awareness, conflict detection, alerting, and guidance to remain well clear.

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1 Introduction

The DANTi concept [3] has been developed at the National Aeronautics and Space Administration (NASA) Langley Research Center to provide a safety enhancing capability for pilots of manned aircraft to remain well clear of other aircraft and avoid potential collisions. DANTi is based on the DAIDALUS Detect and Avoid (DAA) algorithm [1] to provide conflict detection, alerting, and resolution. The DAIDALUS algorithm was developed to address the operational needs of Unmanned Aerial Systems (UAS) and meet the Minimum Operational Performance Standards for Detect and Avoid [2].

Aircraft operating under Visual Flight Rules and not receiving Air Traffic Control radar services rely on see and avoid to remain well clear. Near the vicinity of non-towered airports, pilots could utilize the Common Traffic Advisory Frequency to communicate their position and intentions and to self organize and remain well clear of other aircraft. While the concept of "well clear" (WC) as defined in Title 14 Code of Federal Regulations (14 CFR), Part 91, relies on the subjective perception of the pilot, DAA technologies use a quantified definition of "well clear" based on distance and time parameters, which will be formally presented in Section 3 of this report.

This Contractor Report is organized in the following manner: Section 2 presents the DANTi concept. Section 3 has the definition of well clear and parameter sets. Section 4 is a description of the flight tests using DANTi and presents analysis and results of flight tests that were performed in July and September of 2017. Section 5 introduces the definition of "severity" of encounters risk. Section 6 presents a simulation designed to evaluate the DIADALUS algorithm, definition of scenarios, and simulation analysis and results. Section 7 describes the functioning of a "wrapper" to improve the operational characteristics of the DAIDALUS guidance. Section 8 shows simulation results using an updated version of DAIDALUS. Section 9 contains summary and conclusion.

2 DANTi Concept

The DANTi concept consists of providing information and guidance to the flight crew of a general aviation aircraft to remain well clear of other aircraft. A DANTi prototype has been developed that incorporates a single ADS-B (Automatic Dependent Surveillance-Broadcast) sensor and displays traffic information on an EFB (Electronic Flight Bag). The DANTi prototype receives ownship flight data as well as traffic aircraft states, and uses the DAIDALUS Detect and Avoid algorithm to predict conflicts, generate alerts, and generate guidance. A conflict is defined as a loss of well clear or as a predicted loss of well clear within a given look ahead time. The traffic display on the EFB presents traffic alerts and resolution guidance to the flight crew.

Figure 2-1 shows the EFB display prototype, which provides situational awareness, guidance, and other information. The display shows the ownship blue chevron symbol in the center of the compass rose which in this view is configured to 2.5 nautical miles. A nearby traffic aircraft is shown as a hollow chevron in an amber colored disc indicating that the ownship's current trajectory is in conflict with that traffic aircraft. Traffic aircraft are represented by a white, hollow chevron when they are not in conflict with the ownship.

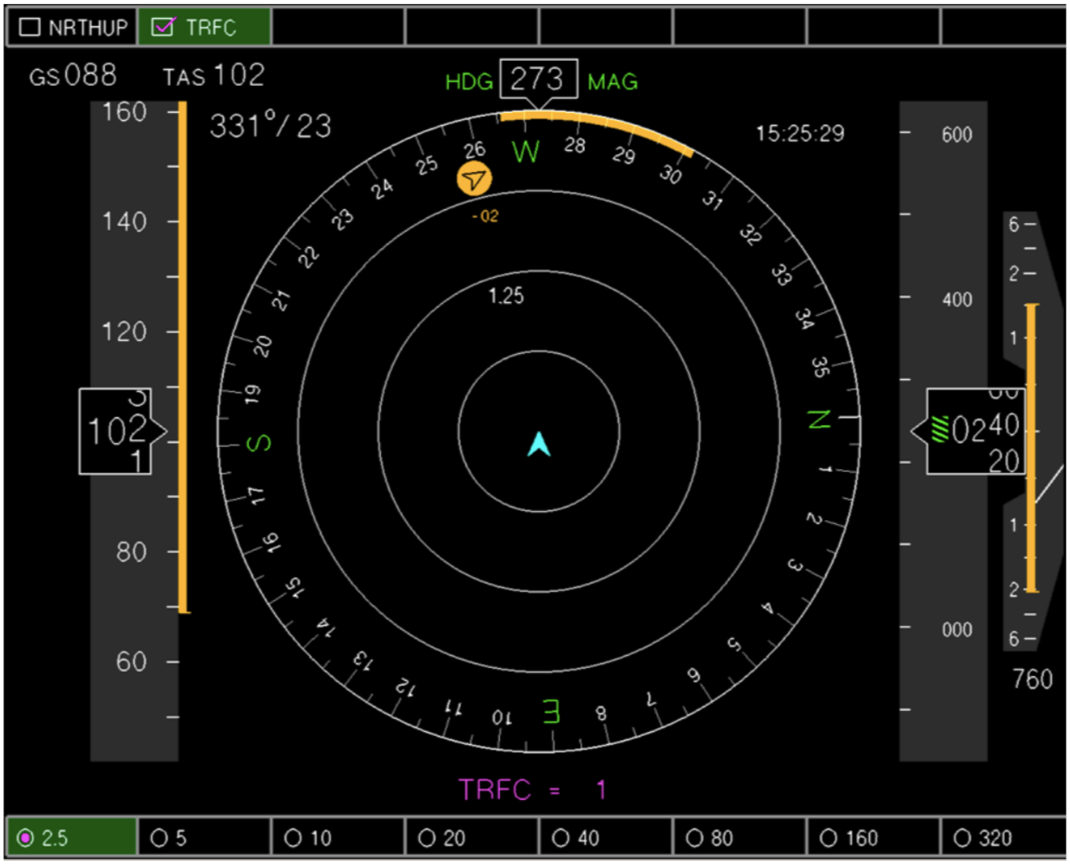


Figure 2-1. DANTi display, version I

The display can be configured to show magnetic heading, magnetic track, true heading or true track at the top of the display, as well as “north” or “track” up. An amber band on the compass rose shows the range of headings that will result in a loss of well clear. For the example in Figure 2-1, the pilot could turn left to a 266-degree heading or turn right to a 302-degree heading to avoid the conflict.

Maneuver guidance is also given for airspeed and rate of climb or descent enabling the pilot to choose the most efficient or safest (single) maneuver to avoid the conflict. Combined maneuvers are not supported in this implementation. However, the pilot could implement combined maneuvers to, for example, turn left to a 266-degree heading and slow down to 69 knots. The display range at the bottom shows that the outer concentric ring is 2.5 nautical miles from the ownship and it can be configured to much larger ranges.

Figure 2-2 shows version II of the DANTi prototype in which a moving map is incorporated in the traffic display background. Two new features are shown in this version: the call signs of the traffic aircraft can be displayed and the scale of the screen can go beyond 2.5 and 320 nautical miles by using the arrows at the corners on the bottom of the display.

Figure 2-2. DANTi prototype display, version II

3 Well Clear Definition and Parameter Set

The code of federal regulations, Title 14, part 91, Section 91.113, paragraph b states:

"*(b)General. When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear.*"

The regulations, however, do not define *well clear* in a quantitative or mathematical way. RTCA Special Committee SC-228 has defined and quantified the notion of well clear to be able to analyze and evaluate operations of Unmanned Aircraft System. Two aircraft are defined to be well clear if they are currently 450 feet or more vertically from one another or if they are projected to be more than 4,000 feet horizontally at all time in their trajectory within the next 35 seconds. Two aircraft are said to have lost well clear when:

$$[0 \le tau_{mod} \le 35\, sec.] \text{and} [HMD \le 4000\,'] \text{and} [-450\,' \le d_h \le 450\,']$$

where,

tau_{mod} is the modified tau, (modified tau is an approximation of the time to the horizontal closest point of approach and is defined below),

HMD is the projected horizontal missed distance at the closest point of approach,

d_h is the vertical distance between the aircraft.

Modified tau is approximately the time to the horizontal closest point of approach and it is defined as follows:

$$tau_{mod} = \begin{cases} \frac{DTHR^2 - r^2}{r\dot{r}} & r > DTHR \\ 0 & r \le DTHR \\ \infty & \dot{r} > 0 \wedge r > DTHR \end{cases} \qquad 3\text{-}1$$

where,

$DTHR$ is the horizontal distance threshold (e.g. 4,000 feet),

r is the horizontal distance between the aircraft,

$\dot{r}$ is the rate of change of the horizontal distance (negative for closure).

The well clear definition uses three parameters which determines the protected volume of the aircraft: horizontal distance threshold, vertical distance threshold, and modified tau or time threshold. Table 3-1 shows the set of parameters that were used in the flight tests to configure the Detect and Avoid (DAA) algorithm in the DANTi prototype. Additional parameters are used to configure the DAIDALUS DAA algorithm and will be discussed in a later section.

Table 3-1. Parameter Threshold Sets

	Set			
Parameter	1	2	3	4
Horizontal distance threshold, DTHR, feet	4000	1200	1200	1200
Vertical distance threshold, ZTHR, feet	450[1]	300[1]	300[1]	300[1]
Time threshold, TTHR, seconds	35	15	0	0

Alerting time, seconds	40	40	40	20

Notes:

1. Due to safety considerations, flight tests were flown with a 500 feet vertical offset. A 1,000 feet vertical threshold was used in all sets to account for the 500 feet safety vertical offset during the runs. Otherwise, the DAA algorithm would not have detected a conflict and the DANTi prototype would not have alerted or provided guidance.

To help visualize the protected volume of an aircraft, Figure 3-1 shows a top view with the protected volume around the ownship highlighted. In this example, the ownship is inside the compass rose at the origin (0.0, 0.0) going west. The traffic aircraft is 9.87 nautical miles west of the ownship (-9.87, 0.0) going east head-on. Aircraft are at co-altitude. The ground speeds of the aircraft are 160 knots and the time to closest point of approach is 111 seconds. For this example, parameter set 1 is used with a time threshold of 35 seconds.

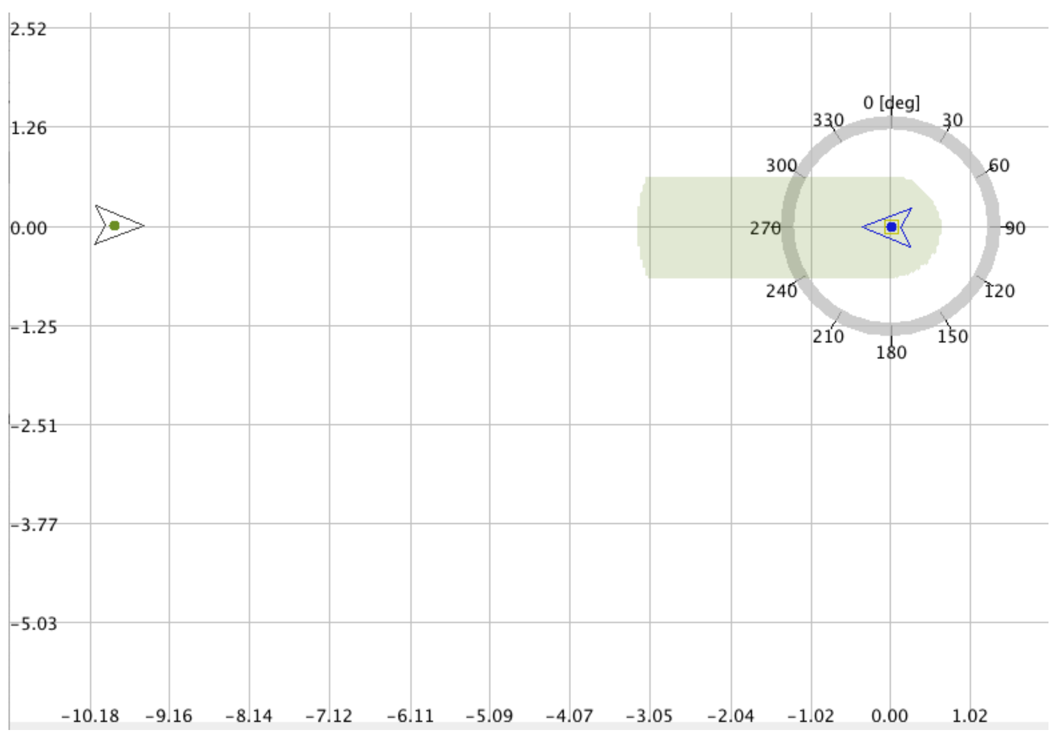


Figure 3-1. Example visualization of the protected volume, time threshold = 35 seconds

The aircraft will lose well clear if the traffic aircraft enters the protected volume of the ownship highlighted in the figure. With the present courses and speeds, this will occur in 68.6 seconds. Note that there is a protected volume around the traffic aircraft which is a mirror image of the protected volume of the ownship and with the same properties.

Figure 3-2 shows the same example as figure 3-1 with the time threshold changed to 0 (zero) seconds. In the example of figure 3-2 with the time threshold equals zero seconds, the aircraft will lose well clear in 103.6 seconds.

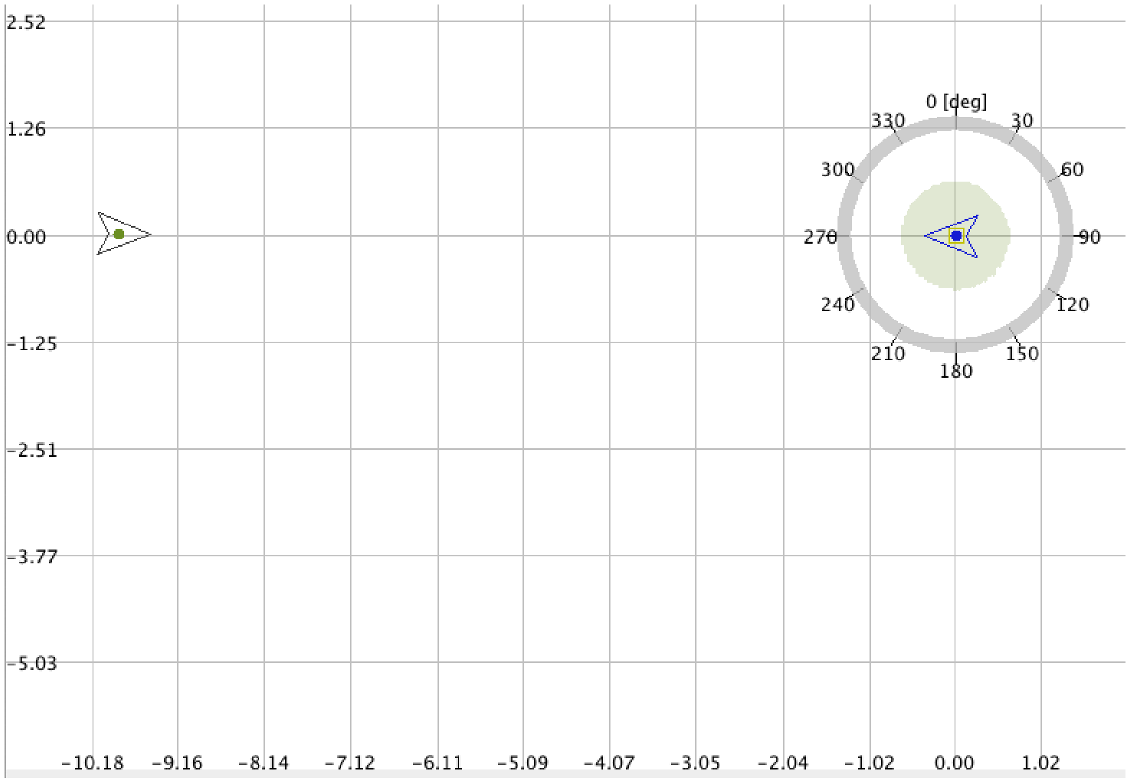


Figure 3-2. Example visualization of the protected volume, time threshold = 0 seconds.

4 Flight Tests

4.1 Flight Test Equipment, Scenarios, and Data

A set of flight tests was conducted by NASA Langley Research Center (LaRC) to evaluate and refine the DANTi concept. The DANTi prototype was installed in NASA's Cirrus SR22 research aircraft. The Cirrus SR22 was used as the ownship and NASA's Cessna 206 aircraft as the traffic aircraft. The flight tests in the Cirrus SR22 included a pilot, a safety pilot, and a research crew monitoring the DANTi EFB. The research crew, amongst other duties, instructed the pilot what maneuvers to perform per the DANTi guidance.

A total of seven flight tests were conducted to evaluate the DANTi concept and prototype. The first two flight tests were conducted in the pattern of Langley Air Force base air field, KLFI, and Wakefield municipal airport, KAKQ. The results of these first two flight tests are documented in [3]. The remaining five test flights were conducted near Wakefield municipal airport (KAKQ), Wakefield, Virginia. This airport is a non-towered airport with light general aviation traffic. Several runs were performed for each flight test with the different parameter sets shown in Table 1. There were three encounter geometries used for these flight tests:

- Head on
- Ninety-degree crossing with traffic flying right to left
- Ninety-degree crossing with traffic flying left to right

The aircraft were in straight, level flight during the encounter runs. For safety reasons, encounters were flown with 500 feet (152 meters) vertical offset between the ownship and the traffic aircraft. Therefore, the vertical distance threshold, ZTHR, was set to 1000 feet (305 meters) to trigger the detection algorithm to detect a conflict and produce guidance. The research crew on-board the ownship aircraft monitored the DANTi EFB and gave the pilot instructions to maneuver to avoid the conflict. In some runs, the guidance produced by DANTi was ignored to observe the progression of the guidance as the two aircraft converged horizontally.

Data was obtained for the seven flight tests. For each time step, the data files contained the DAIDALUS configuration parameters, the state of the aircraft, and the calculations produced by the DAIDALUS algorithm. Appendix A contains a sample of a data file for one time step. Two java programs were developed to extract the data of interest from the data files. The first program extracted the state of the aircraft. The second program extracted the state of the two aircraft that were involved in the flight test encounters. Other aircraft received by the ADS-B sensor (ADS-B in device) were filtered out. The data format for the state of the aircraft and an example is shown in Table 4-1.

Table 4-1. Data format from flight tests

Data Field	Example Value	Description
ACID	A63ED4	A 24 bit ICAO assigned code for the ADS-B transponder. It is represented as a hexadecimal code with each digit representing 4 bits of the 24 bit code.
Latitude	36.86599730	Degrees of latitude North.
Longitude	-76.34899370	Degrees of latitude East. Negative represents West.
Altitude	7150.00000	Pressure altitude in feet as reported by the altitude encoder.
Track	267.187500	Track direction in degrees from the North.
Ground Speed	121.432753	Ground speed in knots.
Vertical Speed	542.000000	Vertical speed in feet per minute.
Time	62775.338821	Time in seconds from midnight. The example shown represents 17:26:15.338821 or 5:26:15.338821PM

4.2 Flight Test Analysis Results

The flight test data was analyzed using the Chorus visualization tool [4]. The Chorus visualization tool can be used to replay the flights from the data files in the format shown in Table 4-1. The tool can be configured with the same parameter set that was used in the flight test and encounter. For the purpose of data analysis, the run started when the track of the aircraft were plus or minus 5 degrees of the intended track. The run ended when the loss of well clear ended or, in the case of no loss of well clear, when the aircraft was observed to turn to position themselves for the next run.

Using the Chorus tool, the following parameters were extracted from the data:

- Type of encounter
- Initial horizontal distance of the encounter
- Time to start of alert and guidance
- Time to start of the maneuver
- Type of maneuver
- Horizontal distance at Closest Point of Approach
-

A total of 41 encounter runs were flown during the five flight tests near Wakefield Municipal airport. Of the 41 encounter runs, the flight crew did not follow the guidance and did not maneuver in 6 encounter runs. These 6 encounter runs were used for adjustment of the encounter trajectories, as the baseline of the flight tests, and to observe the progression of the guidance when no action by the flight crew was taken. The flight crew followed the guidance and performed an avoidance maneuver in 35 of the encounter runs. Tables 4-2 to 4-6 contain a summary of the flight tests results.

Table 4-2. Data file daidalus_063017.150942.txt, 2017 June 30

Run	Param. Set	Geometry	DTHR (feet)	TTHR (seconds)	Time to start maneuver (seconds)	Type of maneuver	Horizontal distance at CPA (feet)	Difference (feet)
1	1	head-on	4000	35	N/A	No evasive	608	-3392
2	1	head-on	4000	35	22	Turn R	3910	-90
3	2	head-on	1200	15	4	Turn L	1660	460
4	3	head-on	1200	0	12	Turn R	1408	208
5	1	Cross R to L	4000	35	5	Turn L	4158	158
6	1	Cross R to L	4000	35	7	Turn R	4118	118
7	1	Cross R to L	4000	35	N/A	No evasive	197	-3803

Table 4-3. Data file daidalus_071817.123243.txt, 2017 July 18

Run	Param. Set	Geometry	DTHR (feet)	TTHR (seconds)	Time to start maneuver (seconds)	Type of maneuver	Horizontal distance at CPA (feet)	Difference (feet)
1	1	Cross R to L	4000	35	N/A	No evasive	142	-3858
2	1	Cross R to L	4000	35	9	Turn R	4003	3
3	1	Cross R to L	4000	35	N/A	No evasive	835	-3165
4	1	Cross R to L	4000	35	8	Turn L	3837	-163

Table 4-4. Data file daidalus_090617.113427.txt, 2017 September 6

Run	Param. Set	Geometry	DTHR (feet)	TTHR (seconds)	Time to start maneuver (seconds)	Type of maneuver	Horizontal distance at CPA (feet)	Difference (feet)
1	1	head-on	4000	35	20	Turn L	3813	-187
2	2	head-on	1200	15	13	Turn R	1530	330
3	2	Cross R to L	1200	15	N/A	No evasive	2553	1353
4	2	Cross L to R	1200	15	N/A	No evasive	2102	902
5	1	Cross R to L	4000	35	19	Turn L	4120	120
6	1	Cross L to R	4000	35	15	Turn R	4207	207

Table 4-5. Data file daidalus_092017.115630.txt, 2017 September 20

Run	Param. Set	Geometry	DTHR (feet)	TTHR (seconds)	Time to start maneuver (seconds)	Type of maneuver	Horizontal distance at CPA (feet)	Difference (feet)
1	1	Cross L to R	4000	35	20	Turn R	7553	3553
2	1	Cross L to R	4000	35	16	Turn R	3994	-6
3	1	Cross L to R	4000	35	17	Turn R	6798	2798
4	1	Cross L to R	4000	35	17	Turn L	4130	130
5	2	Cross L to R	1200	15	16	Turn L	1573	373
6	2	Cross L to R	1200	15	16	Turn R	1065	-135
7	2	Cross L to R	1200	15	18	Turn L	1564	364

8	1	Cross R to L	4000	35	15	Turn L	4067	67
9	1	Cross R to L	4000	35	12	Turn R	4235	235
10	1	Cross R to L	4000	35	19	Turn R	4182	182
11	2	Cross R to L	1200	15	18	Turn R	1642	442
12	2	Cross R to L	1200	15	16	Turn L	1391	191
13	2	Cross R to L	1200	15	17	Turn L	1727	527

Table 4-6. Data file daidalus_092917.163124.txt, 2017 September 29

Run	Param. Set	Geometry	DTHR (feet)	TTHR (seconds)	Time to start maneuver (seconds)	Type of maneuver	Horizontal distance at CPA (feet)	Difference (feet)
1	1	head-on	4000	35	1	Turn L	4781	781
2	1	head-on	4000	35	15	Turn L	4271	271
3	1	head-on	4000	35	14	Turn L	4677	677
4	1	Cross R to L	4000	35	10	Turn L	4190	190
5	1	Cross R to L	4000	35	15	Turn R	4306	306
6	1	Cross L to R	4000	35	10	Turn R	4107	107
7	1	Cross L to R	4000	35	4	Turn R	5689	1689
8	1	Cross L to R	4000	35	21	Turn L	4252	252
9	1	Cross L to R	4000	35	21	Turn R	4174	174
10	1	Cross R to L	4000	35	14	Turn R	4080	80
11	1	Cross R to L	4000	35	11	Turn R	4188	188

Figure 4-1 shows the distribution of horizontal distances at the Closest Point of Approach for the 26 encounters where the horizontal distance threshold was 4,000 feet and the ownship maneuvered following the guidance produced by DANTi. The graph shows that the horizontal distance was never less than 3,800 feet at CPA, 5 cases exceeded 4,500 feet, and the majority of encounters had a distance between 4,100 and 4,200 feet at CPA. Therefore, the intrusion into the protected volume of the traffic aircraft/ownship never exceeded 200 feet.

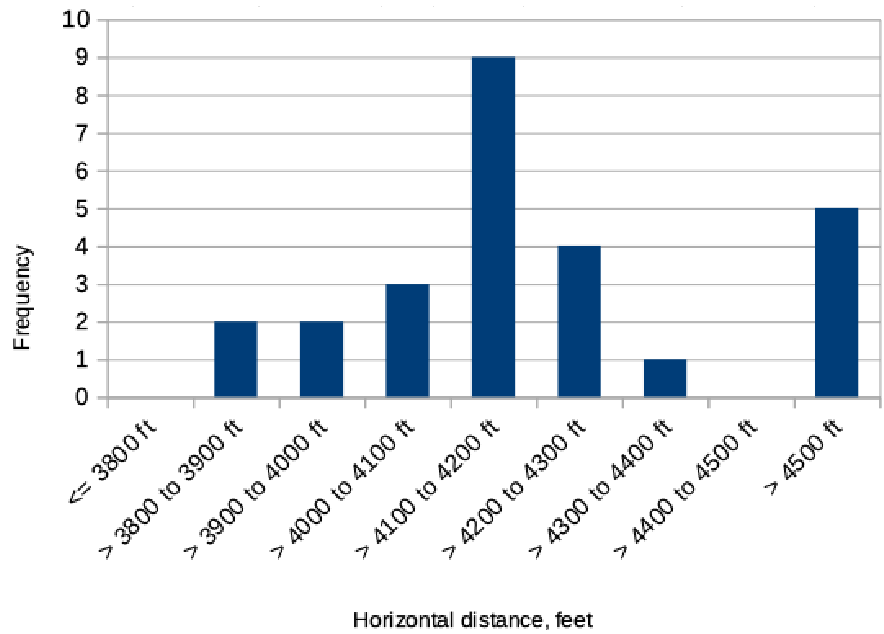


Figure 4-1. Distribution of distances at Closest Point of Approach (CPA), 4,000 feet threshold

Figure 4-2 shows the distribution of horizontal distances at the Closest Point of Approach for the 9 encounters where the horizontal distance threshold was 1,200 feet and the ownship maneuvered following the guidance produced by DANTi. There was one encounter where the distance was less than 1,200 feet with the majority of encounters with a distance between 1,400 and 1,600 at CPA. Similar to when the threshold was 4,000 feet, the intrusion into the protected volume of the traffic aircraft/ownship never exceeded 200 feet.

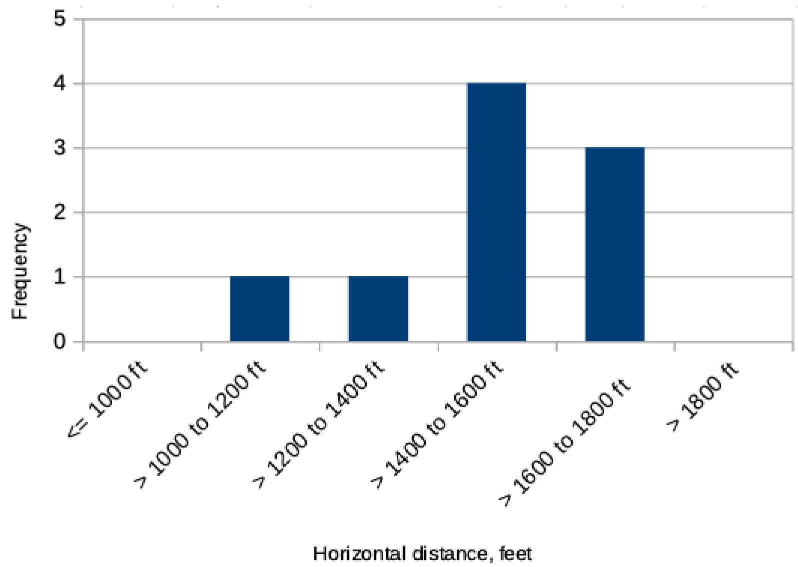


Figure 4-2. Distribution of distances at Closest Point of Approach (CPA), 1,200 feet threshold

Figure 4-3 shows the distribution of time from guidance arrival to guidance implementation for the 35 encounters where the pilot implemented the guidance. The graph shows that the maximum implementation delay time was 22 seconds with a concentration of time delay between 14 and 16 seconds.

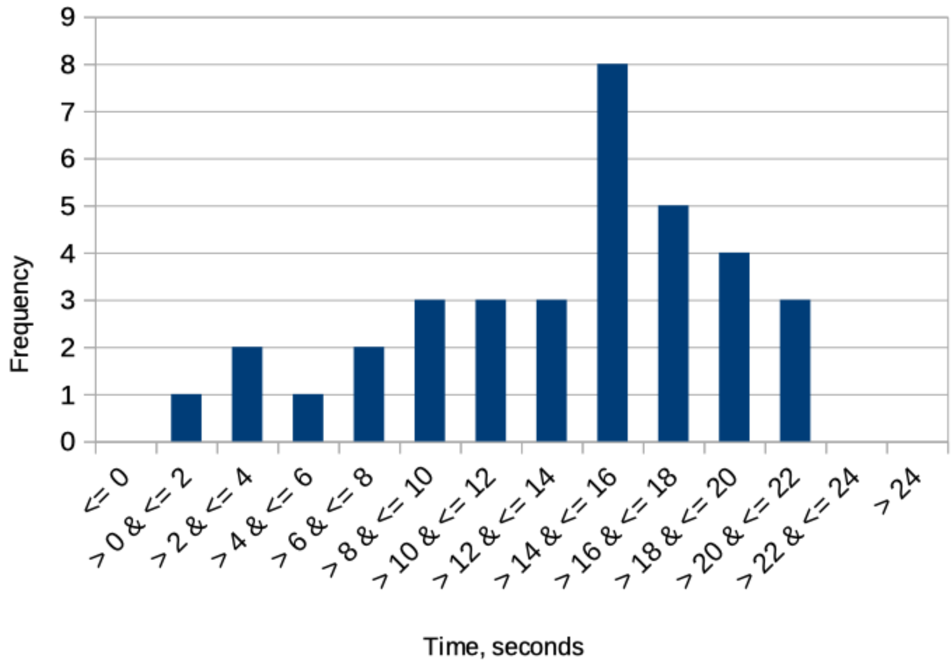


Figure 4-3. Distribution of time between guidance and implementation of maneuver

4.3 Flight Test Analysis Summary

The data analyzed shows that the flight crew of the ownship was able to maneuver with sufficient time to closely achieve the horizontal protected distance (horizontal threshold) at closest point of approach. This was observed with parameters sets 1, 2, and 3. However, only one head-on run was performed with parameter set 3, and more data is needed for this parameter set.

The largest infringement to the protected volume was 187 feet horizontally and this occurred with a head-on scenarios and a 4,000 feet horizontal threshold (parameter set 1).

The guidance produced by DANTi appeared to be less useful when the flight crew did not follow the guidance and the aircraft were allowed to get near the horizontal and/or vertical threshold or when the aircraft were in a loss of well clear situation. This guidance is intended to maintain well clear or re-establish well clear after a loss. It was observed that the guidance tended to change drastically from one second to the next, which could be disconcerting to flight crews that are trying to maintain situational awareness and select a maneuver to maintain well clear. This guidance instability could be the result of variations and errors in the aircraft vertical speeds and also the result of the parameters selected as input to the guidance logic. More analysis was performed using additional scenarios and simulation runs to characterize these conditions. Results and are presented and discussed in Section 6 of this report.

5 Severity

To evaluate encounters and the effectiveness of guidance from a risk viewpoint, severity of an encounter was defined using two methods:

- The Federal Aviation Administration (FAA), Air Traffic Organization (ATO), Safety Management System (SMS) manual [5]
- RTCA Special Committee SC-228 [2]

5.1 FAA ATO's Safety Management System severity

The FAA ATO Safety Management System manual defines severity as follows:

"Severity is the consequence or impact of a hazard's effect or outcome in terms of degree of loss or harm."

The SMS manual further defines Severity in the following categories:

- ATC Services
- Unmanned Aircraft Systems
- Flying Public
- NAS Equipment
- Flight Crew

Table 5-1 is an excerpt of Table 3.3 of the SMS Manual including only the Flight Crew category of the severity definitions listed above.

Table 5-1. Excerpt of severity table from SMS manual pertaining only to flight crews and proximity events

	Hazard Severity Classification				
	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Flight Crew	Pilot is aware of traffic (identified by Traffic Collision Avoidance System traffic alert, issued by ATC, or observed by flight crew) in close enough proximity to	Aircraft is in close enough proximity to another aircraft (identified by Traffic Collision Avoidance System resolution advisory, issued by ATC, or observed by flight crew) to	Aircraft is in close enough proximity to another aircraft (identified by Traffic Collision Avoidance System resolution advisory, issued as a safety alert by ATC, or observed by	Near mid-air collision results due to a proximity of less than 500 feet from another aircraft, or a report is filed by pilot or flight crew member that a collision hazard existed between two or	Mid-air collision.

	require focused attention, but no action is required. Pilot deviation where loss of airborne separation falls within the same parameters of a Proximity Event or measure of compliance greater than or equal to 66 percent.	require specific pilot action to alter or maintain current course/ altitude, but intentions of other aircraft are known and a potential collision risk does not exist. Pilot deviation where loss of airborne separation falls within the same parameters of a Low Risk Analysis Event[1] severity, two or fewer indicators fail.	flight crew) on a course that requires corrective action to avoid potential collision; intentions of other aircraft are not known. Pilot deviation where loss of airborne separation falls within the same parameters of a Medium Risk Analysis Event[1] severity, three indicators fail.	more aircraft. Pilot deviation where loss of airborne separation falls within the same parameters of a High Risk Analysis Event[1] severity, four indicators fail.	

1. Risk Analysis Event severity indicators as follows:
    a. **Proximity.** Failure transition point of 50 percent of required separation or less.
    b. **Rate of Closure.** Failure transition point greater than 205 knots or 2,000 feet per minute (consider both aspects and utilize the higher of the two if one lies above the transition point)
    c. **ATC Mitigation.** ATC able to implement separation actions in a timely manner.
    d. **Pilot Mitigation.** Pilot executes ATC mitigation in a timely manner.

The definition of severity shown in Table 5-1 above is mostly applicable to aircraft operating under air traffic control. However, it shows, in the risk analysis events, that both distance between the aircraft and closure rate are considered in the determination of severity.

5.2 RTCA Special Committee SC-228 severity

A classification of severity pertaining to well clear has also been defined by RTCA SC-228. The definition of severity is based on three components:

1. Horizontal Proximity (tau MOD) (Dynamic component of severity)
2. Horizontal Miss-Distance projection (HMD)
3. Vertical Distance

Each of these 3 components are used in the determination of severity. Each of the components can have a value between 0 (zero), inclusive, and 1 (one), inclusive.

5.2.1 Horizontal Proximity (tau MOD)

The first component of the SC-228 severity definition is given by:

$$RangePen_i = MIN\left(\frac{r_i}{S_i}, 1\right) \quad \text{5-1}$$

where,

$$S_i = MAX\left(DTHR, \frac{1}{2}\sqrt{\left(\dot{r}_i\, tau^*_{mod}\right)^2 + 4\, DTHR^2} - \dot{r}_i\, tau^*_{mod}\right) \quad , \quad \text{5-2}$$

$DTHR$ is the horizontal distance threshold (e.g. 4,000 feet),

tau^*_{mod} is the time threshold TTHR (e.g. 35 seconds),

r is the horizontal distance between the aircraft,

$\dot{r}$ is the rate of change of the horizontal distance (negative for closure).

5.2.2 Horizontal Miss-distance Projection (HMD)

The second component of the SC-228 severity definition is given by:

$$HMDPen_i = MIN\left(\frac{HMD_i}{DTHR}, 1\right) \quad \text{5-3}$$

where,

$$HMD_i = \begin{cases} \sqrt{\left(d_x + v_{rx} t_{CPA}\right)^2 + \left(d_y + v_{ry} t_{CPA}\right)^2}\Big|_i & t_{CPA} > 0 \\ r_i & t_{CPA} \le 0 \end{cases} \quad , \quad \text{5-4}$$

$t_{CPA} = \dfrac{-d_x v_{rx} + d_y v_{rx}}{v_{rx}^2 + v_{ry}^2}$ is the time to horizontal Closest Point of Approach, 5-5

d_x is the distance difference between aircraft in the x axis,

d_y is the distance difference between aircraft in the y axis,

v_{rx} is the relative speed between aircraft in the x axis,

v_{ry} is the relative speed between aircraft in the y axis.

5.2.3 Vertical Distance

The third component of the SC-228 severity definition is given by:

$$VertPen_i = MIN\left(\frac{dh_i}{H^*}, 1\right) \quad 5\text{-}6$$

where,

H^* is the vertical distance threshold, ZTHR (e.g. 450 feet),

dh_i is the relative altitude between aircraft.

5.2.4 Severity Definition

The severity of an encounter is defined by:

$$SLoWC = MAX(SLoWC_i) \forall i \quad 5\text{-}7$$

where,

$$SLoWC_i = (1 - RangePen_i \oplus HMDPen_i \oplus VerPen_i) \times 100\% \quad , \quad 5\text{-}8$$

$$x \oplus y = \sqrt{(x^2 + y^2 - x^2 y^2)} \quad , \quad 5\text{-}9$$

i is the time step of the encounter.

That is, for all the time steps of an encounter, the severity of the encounter is the highest time step severity. The severity of an encounter as defined by equation 5-7 can have values from 0 percent to 100 percent, with 0 percent representing the least severity and 100 percent the highest severity.

The operator $\oplus$ was first proposed by Anthony Narkawicz and Cesar Muñoz as the norm operator to combine the three components of severity [2]. The operator $\oplus$ is a special case of the "squircle" defined by Fernandez Guasti in [6]. The general equation of the "squircle" is:

$$s^2 \frac{x^2}{k^2} \frac{y^2}{k^2} - \left(\frac{x^2}{k^2} + \frac{y^2}{k^2}\right) + 1 = 0 \quad 5\text{-}10$$

If we limit equation 5-10 to $x^2 \le k^2$ and $y^2 \le k^2$, then, when $s=0$, equation 5-10 represents a circle of radius k and when $s=1$, equation 5-10 represents a square with side lengths equal 2k. The special case of equation 5-10 is when we let $s=k$:

$$\frac{x^2 y^2}{k^2} - \left(\frac{x^2}{k^2} + \frac{y^2}{k^2}\right) + 1 = 0 \qquad \text{5-11}$$

Rearranging the terms in equation 5-11 we obtain:

$$x^2 + y^2 - x^2 y^2 = k^2 \qquad \text{5-12}$$

Plotting equation 5-12 in the first quadrant of the cartesian plane for values of k from 0 to 1 in increments of 0.1, we obtain the graph shown in Figure 5-1.

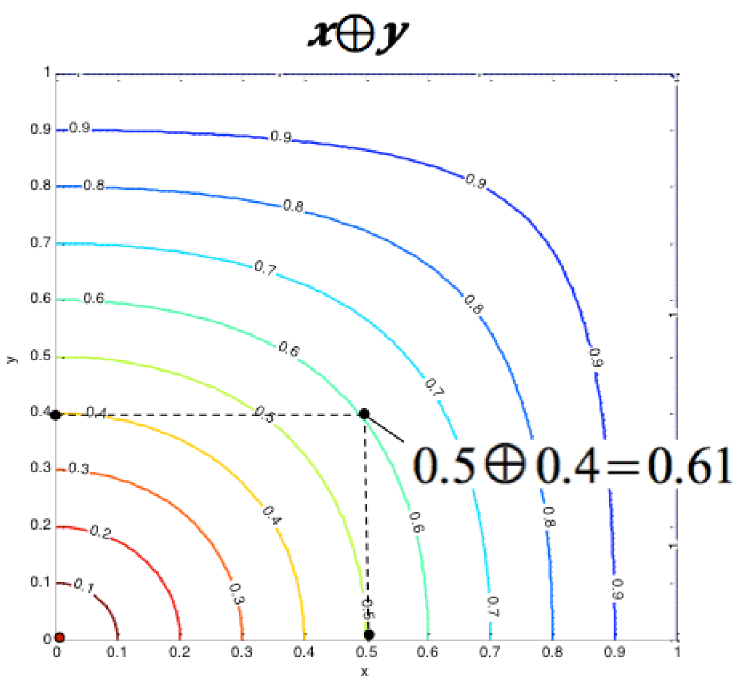


Figure 5-1. Special case of "squircle" with s=k and values of k from 0 to 1

Figure 5-1 shows an example of the norm operator $\oplus$ for values of x=0.5 and y=0.4 resulting in a value of 0.61.

5.2.5 Mapping of SC-228 definition of severity to SMS severity

A conservative approach is used to map the SC-228 definition of Severity of Loss of Well Clear

(SLoWC) to the Safety Management System (SMS) severity. The conservative approach is to use the higher severity of the SMS manual when a percentage of SLoWC could map to more than one severity. Table 5-2 shows the mapping.

Table 5-2. Mapping of severity from SC-228 to SMS Classification

SC-228 Severity Levels	SMS Severity Classification
0%-17%	5, Minimal
17%-33%	4, Minor
33%-47%	3, Major
47%-94%	2, Hazardous
94%-100%	1, Catastrophic

6 Encounter Simulations

This section presents the simulation design and results of the simulated encounters where the DAIDALUS algorithm is used to detect encounter conflicts and generate resolutions to resolve the conflicts. The objective of the encounter simulations was to evaluate the DAIDALUS algorithm in a variety of scenarios and in a statistical manner by adding randomness to the scenarios and performing thousands of simulation runs.

A virtual pilot was developed and used as part of the simulations. The virtual pilot receives the resolutions generated by DAIDALUS and implements the resolutions after a configurable delay which is defined by a random variable distribution. The virtual pilot can also be configured to select whether the resolutions implemented are horizontal direction or vertical speed resolutions, and the type of horizontal (left, right, smallest) or vertical resolution (up, down, smallest relative, smallest absolute).

Figure 6-1 shows a flow diagram of the simulation program. Each scenario represents a set of initial conditions (nominal initial state), to which random values are added to specific parameters (location, horizontal speed, vertical speed, etc.) for each simulation run, which then defines the initial state of the simulation run.

The state of the system is updated at a 1 Hz (Hertz) rate by the dynamics module. The virtual pilot receives the alerts and resolutions generated by DAIDALUS, implements the resolutions, and sends the commands to the dynamics module. The dynamics module uses the current state and wind conditions to generate the next state of the system. The encounter severity module determines the severity of the encounter based on all the states of the simulation run, as defined by Equation 5-7.

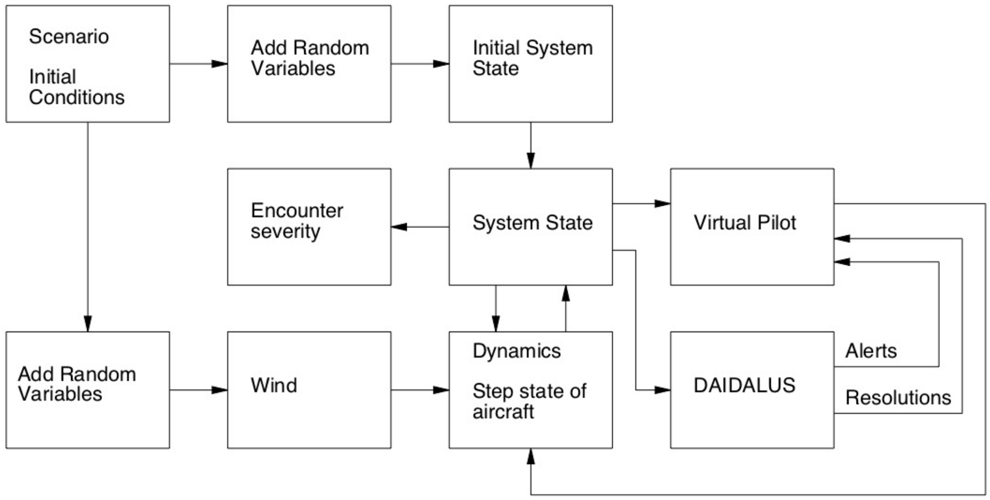


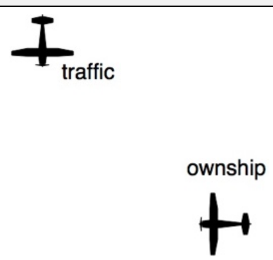
Figure 6-1. Simulation structure flow diagram

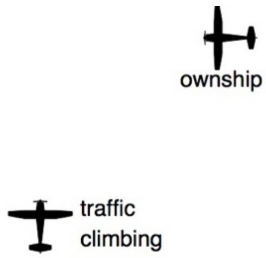
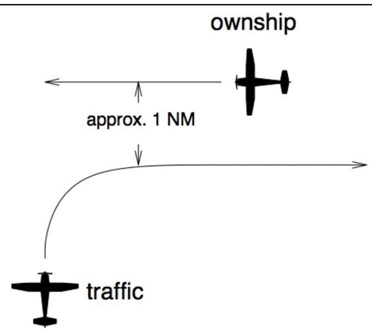
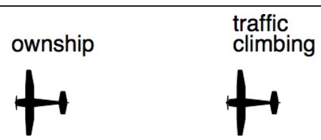
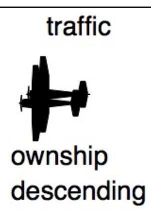
6.1 Scenarios

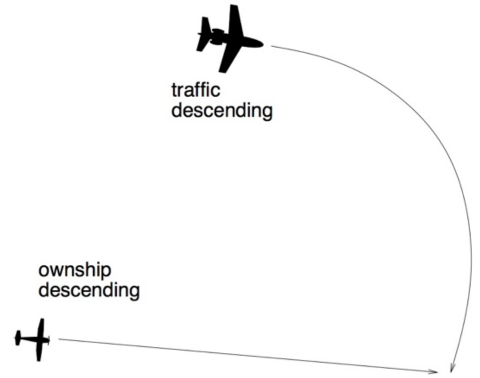
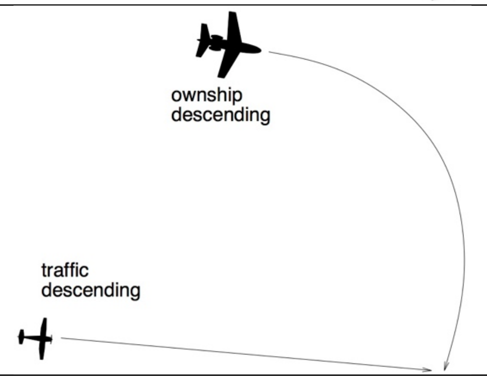
The scenarios define the initial condition geometry and speeds of the encounter. Table 6-1 shows the initial condition geometry and state of the aircraft with nominal values of range, horizontal direction, altitude, and vertical speed. The values in the table are nominal values. The initial system state for each run are the nominal values plus a random variable with Gaussian (Normal) distribution as follows:

- Horizontal direction = nominal + *X* (0 mean, 1 degree standard deviation)
- Latitude = nominal + *X* (0 mean, 50 meters s.d.)
- Longitude = nominal + *X* (0 mean, 50 meters s.d.)
- Horizontal speed = nominal + *X* (0 mean, 5 knots s.d.)
- Altitude = nominal + *X* (0 mean, 50 feet s.d.)
- Vertical speed = nominal + *X* (0 mean, 25 feet/min. s.d.)

Table 6-1. Scenarios with nominal values, O: ownship T: traffic aircraft

Scenario	Geometry	Range, nautical miles	Horizontal direction, degrees	Horizontal speed, knots	Altitude, feet.	Vertical speed, feet/min
1		6.97	O = 270 T = 180	O = 160 T = 160	O = 6,500 T = 6,500	O = 0 T = 0

2		6.97	O = 270 T = 360	O = 160 T = 160	O = 6,500 T = 5,572	O = 0 T = 500
3		9.11	O = 270 T = 135	O = 160 T = 160	O = 5,572 T = 6,500	O = 500 T = 0
4		9.87	O = 270 T = 90	O = 160 T = 160	O = 6,500 T = 6,500	O = 0 T = 0
5		7.21	O = 270 T = 0 to 90	O = 160 T = 160	O = 6,500 T = 6,500	O = 0 T = 0
6		1.01	O = 270 T = 270	O = 130 T = 160	O = 6,500 T = 5,500	O = 0 T = 500
7		0.0	O = 270 T = 270	O = 160 T = 160	O = 8,500 T = 6,500	O = -500 T = 0

8a		0.841 (5,109 feet)	O = 95 T = 100	O = 93 T = 129	O = 1483 T = 1993	O = -356 T = -1,330
8b		0.841 (5,109 feet)	O = 100 T = 95	O = 129 T = 93	O = 1993 T = 1483	O = -1,330 T = -356

Scenario 8 is a recreation and approximation of an encounter that resulted in a mid-air collision [7]. The accident occurred on the 16th of August 2015 at Brown Field Municipal Airport (KSDM), San Diego, California. The aircraft involved were a Cessna 172 (N1285U) conducting touch-and-go operations, and an experimental North American Rockwell Sabreliner (N442RM) returning to KSDM from a mission flight. Figure 6-2 shows the radar path of the aircraft (from the NTSB report, reference [7], in public domain). Scenario 8 reconstruction starts at time 11:02:40 PDT or 30.2 seconds before the collision. At this time, the Cessna 172 is at an altitude of 1,483 feet above mean sea level (MSL) and the Sabreliner is at 1,993 feet MSL.

Figure 6-2. Trajectories of aircraft involved in mid-air collision

Scenario 8a has the Cessna 172 as the ownship and implementing the DAIDALUS resolutions in the simulation runs. Scenario 8b has the Sabreliner as the ownship and implementing the DAIDALUS resolutions. In scenario 8b, the ownship is turning and will continue to turn until the virtual pilot implements the resolution advisory.

6.2 DAIDALUS Guidance

The DAIDALUS algorithm is invoked with the current states of the aircraft. The DAIDALUS algorithm produces alerting and resolution guidance. Alerting and guidance include horizontal direction, horizontal speed, vertical speed, and altitude. In the simulation presented in this paper, only the horizontal direction and vertical speed are used as guidance. Preliminary experiments showed that horizontal speed alone is ineffective in solving conflicts with encounters that are 60 to 120 seconds from the closest point of approach. Altitude resolution (establishing vertical distance between the aircraft) is a by-product of vertical speed and is implemented by control of the vertical speed.

The alerting and guidance produced by DAIDALUS are passed to the virtual pilot part of the simulation to implement the guidance. For the simulations and results presented in this paper, DAIDALUS has been configured using the parameters contained in Appendix A of this paper.

6.3 Virtual Pilot

The virtual pilot receives the alerting and guidance generated by the DAIDALUS algorithm and implements the guidance. The guidance is implemented by sending a new vertical speed or new heading to the Dynamics module of the simulation. The virtual pilot is configured with the parameters shown in Table 6-2.

Table 6-2. Configuration parameters for virtual pilot

Parameter	Values	Parameter description
Resolution type	*none, horizontal, vertical, both*	*None* means no resolution will be implemented, *horizontal* implements horizontal direction resolutions, *vertical* implements vertical speed resolution, and *both* implements simultaneous horizontal and vertical resolutions.
Horizontal direction resolution type	*smallest, turn right, turn left*	When horizontal resolution is selected, *smallest* will implement the heading change that solves the conflict by turning the least amount. *turn right* will force the virtual pilot to select the resolution that solves the conflict by turning right, even if it requires a greater change in direction than turning left. The virtual pilot checks if there is a valid resolution to the right. If there is not, virtual pilot turns left. *turn left* is similar to *turn right* but in the counter clockwise direction.
Vertical speed resolution type	*smallest change, increase, decrease, smallest absolute*	When vertical resolution is selected, *smallest change* will implement the smallest change in vertical speed with reference to the current vertical speed. Selecting *increase* will increase (makes more towards positive) the climb/descent rate with reference to the current vertical speed[1]. Selecting decrease will decrease (makes it more towards negative) the climb/descent rate with reference to the current vertical speed. Selecting *smallest absolute* will implement the least vertical speed with reference to level flight (zero vertical speed).

Note: 1. Increasing the vertical speed could result in a negative vertical speed if the aircraft was descending before the implementation of the guidance. For example, if the aircraft has a vertical speed of -800 feet/minute and the guidance is to increase speed by 500 feet/minute, the new vertical speed will be a descent rate of -300 feet/minute.

Horizontal direction changes are implemented at a 3 degrees per second turn rate. For example, if the ownship horizontal direction is 070 degrees and the resolution is turn right to 110 degrees, then the virtual pilot will change the direction to 073 degrees the first second, to 076 degrees the second second, 079 degrees the third second, etc.

Vertical speed changes are implemented within one second and are limited to the aircraft's maximum climb rate. The maximum climb rate used for the simulations presented in this paper are based on a Lancair LC40-550FG at maximum gross takeoff weigh of 3,400 lbs., sea level pressure altitude, and International Standard Atmosphere (ISO). The corresponding maximum climb rate is 1,225 feet per minute. A maximum descent rate of -1,225 feet per minute is also used. When the vertical speed guidance exceeds the maximum climb or descent rate, the virtual pilot implements the maximum climb or descent rate in the direction of the selected vertical speed resolution type.

When the virtual pilot receives a conflict alert, it will implement a resolution after a time delay (except when the resolution type = *none*, in which case no resolution will be implemented). The delay from the time the ownship is in a conflicting trajectory (alert) to the time the virtual pilot implements the resolution is defined by a random variable with a Rayleigh distribution. The probability density function of a Rayleigh distribution is given by,

$$f(x|\sigma)=\frac{x\,e^{\left(\frac{-x^2}{2\sigma^2}\right)}}{\sigma^2} \qquad \text{6-1}$$

The expected value or mean of the distribution is given by,

$$\text{Mean} = \sigma\sqrt{\frac{\pi}{2}} \qquad \text{6-2}$$

Figure 6-3 shows the probability density function of a Rayleigh distribution with $\sigma=3.989$ and mean value = 5.

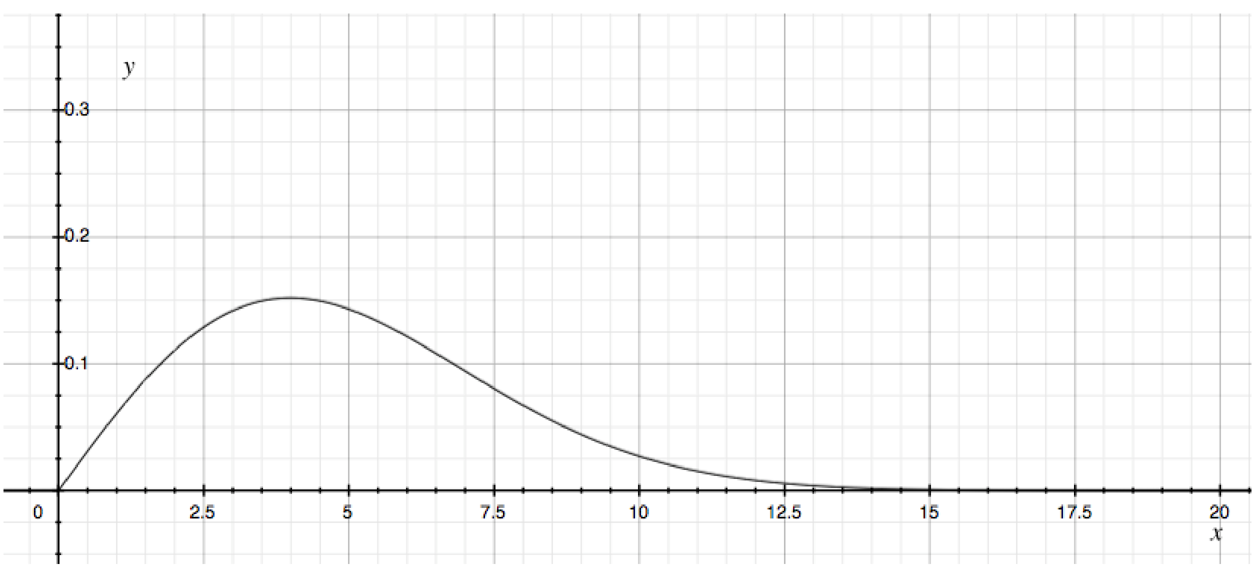


Figure 6-3. Rayleigh probability density function

6.4 Dynamics

The dynamics part of the simulation takes the states of the aircraft and the inputs from the virtual pilot and computes new states. The new states are calculated in one second intervals using the current location of the aircraft, horizontal direction, horizontal speed, altitude, and vertical speed.

6.5 Simulation Results, Encounters with No Wind, DAIDALUS version 2.0.2b

Simulations were run for the eight scenarios shown in Table 6-1. Scenario 8 was run interchanging the ownship and traffic aircraft as scenarios 8a and 8b. For each scenario, 10,000 simulations runs were performed for each of the following conditions for a total of 440,000 simulation encounters with no wind:

- No resolution maneuver
- Horizontal resolution (smallest direction change)
- Vertical resolution (smallest absolute vertical speed)
- Five seconds average pilot's delay
- Fifteen seconds average pilot's delay

Table 6-3 has the encounter results when the virtual pilot follows the horizontal direction resolution guidance. The selected type of horizontal resolution is the one that changes the current direction the least. The ownship implements the horizontal direction resolution at a 3 degrees per second turn rate.

Table 6-3. Results, horizontal direction resolution guidance, DAIDALUS version 2.0.2b

		Severity					
Scenario	Resolution delay, mean	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
1	No res	0.04%	0.31%	2.26%	8.16%	86.44%	2.79%
	15 sec.	21.5%	62.2%	14.0%	2.02%	0.28%	0
	5 sec.	54.0%	46.0%	0	0	0	0
2	No res	0.01%	0.35%	2.17%	7.15%	87.23%	3.09%
	15 sec.	41.3%	54.7%	3.49%	0.48%	0.09%	0
	5 sec.	76.4%	23.6%	0	0	0	0
3	No res	0	0.03%	0.78%	3.68%	91.8%	3.74%
	15 sec.	37.1%	58.3%	4.00%	0.46%	0.10%	0
	5 sec.	83.2%	16.8%	0	0	0	0
4	No res	0	0	0.37%	2.88%	92.7%	4.05%
	15 sec.	23.6%	58.7%	14.7%	2.64%	0.29%	0
	5 sec.	83.6%	16.4%	0	0	0	0
5	No res	0	1.72%	44.6%	49.2%	4.48%	0
	15 sec.	4.13%	32.1%	55.3%	4.86%	3.53%	0
	5 sec.	9.47%	31.8%	56.8%	0.99%	0.92%	0
	No res	0.08%	1.08%	4.54%	11.7%	80.2%	2.37%

6	15 sec.	15.4%	82.8%	1.67%	0.07%	0.01%	0
	5 sec.	43.9%	56.1%	0	0	0	0
7	No res	9.73%	36.9%	17.8%	12.6%	22.6%	0.31%
	15 sec.	41.9%	57.3%	0.72%	0.04%	0	0
	5 sec.	92.3%	7.7%	0	0	0	0
8a	No res	0	0	0	0.11%	87.1%	12.8%
	15 sec.	0	0.01%	0.44%	4.12%	93.7%	1.72%
	5 sec.	0	0.01%	0.98%	8.39%	90.62%	0
8b	No res	0	0	0	0.11%	87.1%	12.8%
	15 sec.	0	18.7%	14.9%	11.9%	52.9%	1.62%
	5 sec.	0	79.9%	16.6%	2.72%	0.79%	0

Table 6-4 has the encounter results when the virtual pilot follows the vertical speed resolution guidance. The selected type of vertical resolution is the smallest absolute value of the vertical speed, regardless of the current vertical speed of the ownship. For example, if the resolution is to climb at 700 feet/min. or to descend at 800 feet/min., the virtual pilot will implement the 700 feet/min climb, regardless of whether the ownship is currently climbing, descending, or on level flight.

The virtual pilot implements the vertical speed resolution up to the maximum climb rate of the aircraft. For the simulation results shown in Table 6-4, the maximum climb rate was set at 1,225 feet per minute. If the vertical speed resolution exceeds the maximum climb rate, the virtual pilot will implement a 1,225 feet climb or descent rate as the resolution.

Table 6-4. Results, vertical speed resolution guidance, DAIDALUS version 2.0.2b

		Severity					
Scenario	Resolution delay, mean	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
1	No res	0.04%	0.31%	2.26%	8.16%	86.44%	2.79%
	15 sec.	0.04%	70.0%	26.5%	3.18%	0.28%	0
	5 sec.	0.04%	99.95%	0.01%	0	0	0
2	No res	0.01%	0.35%	2.17%	7.15%	87.23%	3.09%
	15 sec.	48.4%	47.9%	3.08%	0.49%	0.08%	0
	5 sec.	83.48%	16.52%	0	0	0	0
3	No res	0	0.03%	0.78%	3.68%	91.8%	3.74%
	15 sec.	42.85%	52.73%	3.77%	0.51%	0.14%	0
	5 sec.	78.64%	21.36%	0	0	0	0
4	No res	0	0	0.37%	2.88%	92.7%	4.05%
	15 sec.	0	66.03%	29.3%	4.22%	0.41%	0

	5 sec.	0	99.97%	0.03%	0	0	0
5	No res	0	1.72%	44.6%	49.2%	4.48%	0
	15 sec.	0	58.21%	34.1%	6.97%	0.70%	0
	5 sec.	0	98.53%	0.50%	0.76%	0.21%	0
6	No res	0.08%	1.08%	4.54%	11.7%	80.2%	2.37%
	15 sec.	94.81%	4.96%	0.22%	0.01%	0	0
	5 sec.	99.42%	0.58%	0	0	0	0
7	No res	9.73%	36.9%	17.8%	12.6%	22.6%	0.31%
	15 sec.	95.98%	3.89%	0.13%	0	0	0
	5 sec.	100%	0	0	0	0	0
8a	No res	0	0	0	0.11%	87.1%	12.8%
	15 sec.	0.54%	5.24%	12.2%	16.8%	63.0%	2.23%
	5 sec.	2.44%	23.10%	33.9%	24.6%	15.9%	0
8b	No res	0	0	0	0.11%	87.1%	12.8%
	15 sec.	2.66%	17.7%	17.6%	14.4%	44.0%	3.59%
	5 sec.	13.2%	66.5%	16.6%	2.73%	0.97%	0

Table 6-5 shows the combined results for encounter scenarios where the ownship and traffic aircraft are at co-altitude and straight and level flight, scenarios 1 and 4. The table shows the severity when there is no resolution, horizontal resolution with a 5 seconds average pilot delay, and vertical resolution with a 5 seconds average pilot delay. For the horizontal resolution, all encounters have no loss of well clear or Minimal severity. For the vertical resolution, the large majority of encounters have Minimal severity with 0.02% having no loss of well clear and Minor severity. For these type of scenarios, the horizontal resolution produces slightly better results.

Table 6-5. Scenarios at co-altitude, straight and level flight, 5 seconds average pilot delay, Scenarios 1 and 4

Resolution type	Severity					
	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
No resolution	0.02%	0.16%	1.32%	5.52%	89.57%	3.42%
Horizontal	68.8%	31.2%	0	0	0	0
Vertical	0.02%	99.96%	0.02%	0	0	0

Table 6-6 shows the combined results of encounters when the ownship or traffic aircraft are climbing or descending, scenarios 2, 3, 6, and 7. Both the horizontal and vertical resolution produce good results with all encounters having either no loss of well clear or Minimal severity. For these type of scenarios, the vertical resolution produces slightly better results.

Table 6-6. Climbing or descending scenarios, 5 seconds average pilot delay, Scenarios 2, 3, 6, and 7

Resolution type	Severity					
	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
No resolution	2.46%	9.59%	6.32%	8.78%	70.5%	2.38%
Horizontal	74.0%	26.0%	0	0	0	0
Vertical	90.39%	9.62%	0	0	0	0

Table 6-7 shows the results of scenarios where the ownship or traffic are turning, scenarios 5, 8a, and 8b. These scenarios, and specifically scenarios 8a and 8b are severe scenarios with 8.53 percent of the encounters resulting in a potential collision if no action is taken by the aircraft. For the 30,000 simulation encounter runs, both the horizontal and vertical resolutions eliminated the potential for collisions. However, the scenarios still resulted in a large number of severity 2 (Hazardous) encounters. For these turning scenarios, the vertical resolution was significantly more effective than the horizontal resolution. Encounters of severity 2 were reduced by a factor of 2 when horizontal resolutions were used and reduced by a factor of more than 10 when vertical resolutions were used.

Table 6-7. Turning scenarios, 5 seconds average pilot delay, Scenarios 5, 8a, and 8b

Resolution type	Severity					
	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
No resolution	0	0.57%	14.87%	16.47%	59.56%	8.53%
Horizontal	3.16%	37.24%	24.79%	4.03%	30.78%	0
Vertical	5.21%	62.71%	17.00%	9.36%	5.69%	0

The DAIDALUS resolutions significantly reduce the probability of a collision and the severity of the encounters, even when the virtual pilot delays the implementation of the resolution by an average of 15 seconds. For example, for scenario 1, there are 86.44% encounters of severity 2 when no resolution is implemented and this is reduced to 0.28% encounters of severity 2 with a 15 seconds average pilot delay, or a factor of more than 300.

Scenarios where the aircraft are in straight and level flight at co-altitude and scenarios where the aircraft are in straight flight climbing or descending give similar results and the resolutions are highly effective in avoiding collisions and reducing severity. Scenarios where the aircraft are turning are the most challenging in avoiding collisions and reducing the severities of the encounters.

6.6 Simulation Results, Encounters in the Presence of Wind, DAIDALUS version 2.0.2b

After evaluation of the DIADALUS algorithm with no wind scenarios, wind was introduced in the simulations to evaluate the algorithm under more realistic conditions. A wind analysis was performed using data covering the continental United States to characterize wind magnitude. The data was obtained from the Aviation Weather Center, National Oceanic and Atmospheric Administration (NOAA), National Weather Service. The results of the analysis are shown in Appendix C of this document. The analysis shows that the average magnitude of the winds aloft over the continental United States are:

- At 6,000 feet above mean sea level: 21.80 knots
- At 12,000 feet above mean sea level: 33.94 knots
- At 18,000 feet above mean sea level: 49.04 knots

Because most light, single engine, unpressurized, general aviation aircraft fly at 12,000 feet MSL or below, a wind magnitude of 50 knots is used as a conservative estimate of a strong wind scenario to be encountered by a light general aviation aircraft.

Scenario 1 (Sub-section 6.1, Table 6-1) was evaluated and compared with and without wind using the following wind conditions:

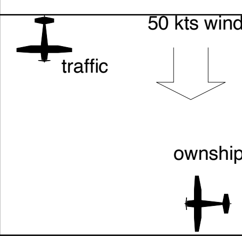
- Scenario 1. No wind
- Scenario 1a. 50 knots wind from the north (wind vector 0,-50,0)
- Scenario 1b. 50 knots wind from the south (wind vector 0, 50, 0)
- Scenario 1c. 50 knots wind from the north-west (wind vector 35.356, -35.356, 0)
- Scenario 1d. 50 knots wind from the south-east (wind vector -35.356, 35.356, 0)
- Scenario 1e. 50 knots from a random direction

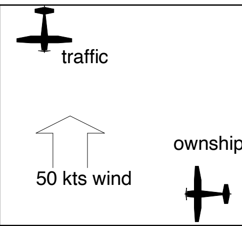
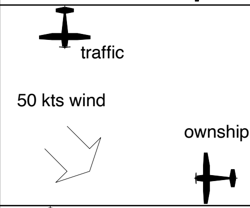
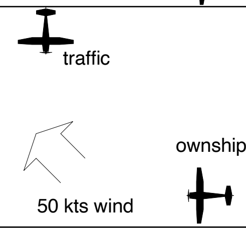
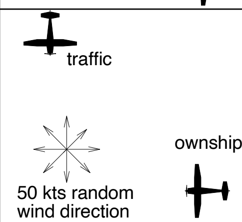
The wind vector is the (x, y z) component vector where,

- x component is in the east-west direction with the positive x component pointing east,
- y component is in the north-south direction with the positive y component pointing north,
- z component is the vertical component.

Table 6-8 shows the graphical representation of the wind scenarios.

Table 6-8. Wind scenarios

Scenario	Wind	Geometry
1	No wind	
1a	50 knots from the north (x,y,z) vector = (0, -50, 0)	

1b	50 knots from the south (x,y,z) vector = (0, 50, 0)	
1c	50 knots from the north-west (x,y,z) vector = (35.356, -35.356, 0)	
1d	50 knots from the south-east (x,y,z) vector = (-35.356, 35.356, 0)	
1e	50 knots from a random direction (x,y,z) vector = (X, Y, 0) where $X^2 + Y^2 = 50^2$	

Ten thousand simulation runs were performed for the scenario with no wind and for each of the scenarios with winds in different directions. Table 6-9 shows the results for these scenarios.

Table 6-9. Scenarios 1 to 1e, 5 seconds average pilot delay, DAIDALUS version 2.0.2b

		Severity, SMS					
Scenario	Wind out of (vector)	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
1	No wind (0,0,0)	89.51%	10.49%	0	0	0	0
1a	North (0,-50,0)	87.36%	12.64%	0	0	0	0
1b	South (0,50,0)	92.30%	7.7%	0	0	0	0
1c	North-west (35,-35,0)	86.42%	13.58%	0	0	0	0
1d	South-east (-35,35,0)	92.23%	6.77%	0	0	0	0

1e	50 knots random	89.72%	10.28%	0	0	0	0

The results of the simulations show that all wind scenarios have a severity of Minimal or there is No Loss of Well clear. This means that when the DAIDALUS resolution is implemented, the maneuver is effective in solving the conflict in scenarios where wind is taken into consideration. When all wind directions are considered, such as Scenario 1e where the wind direction is random, the results are statistically equal to the scenario with no wind.

Although wind does not have a detrimental effect on the safety of the DAIDALUS resolution maneuver, an undesirable effect on operations was observed during simulation runs. This undesirable effect is discussed in the next sub-section.

6.7 Detrimental Operational Effect of DAIDALUS Resolution Guidance

The simulation results show that the DAIDALUS resolutions effectively solve the conflicts. However, there is a potential undesirable characteristic and secondary effect of the conflict guidance. These characteristics and secondary effects are:

1. Depending on the resolution selected by the pilot (turn right or turn left), the guidance provided by DAIDALUS might fluctuate as the ownship implements the resolution. As the resolution guidance is implemented, the guidance might disappear indicating that no conflict exists and re-appear at a later time indicating that further action is needed.

2. Depending on the resolution selected by the pilot (turn right or turn left), the ownship might have to make a large deviation from its intended trajectory to solve the conflict. This large deviation is not apparent from the initial resolution guidance.

These issues are due to the change in time to loss of well clear when the ownship starts implementing the resolution guidance. The situation is more pronounced when the resolution maneuver causes a significant change in ground speed due to wind conditions.

The following example illustrates the characteristic and secondary effects issues presented above. The scenario and initial conditions are shown in figure 6-4.

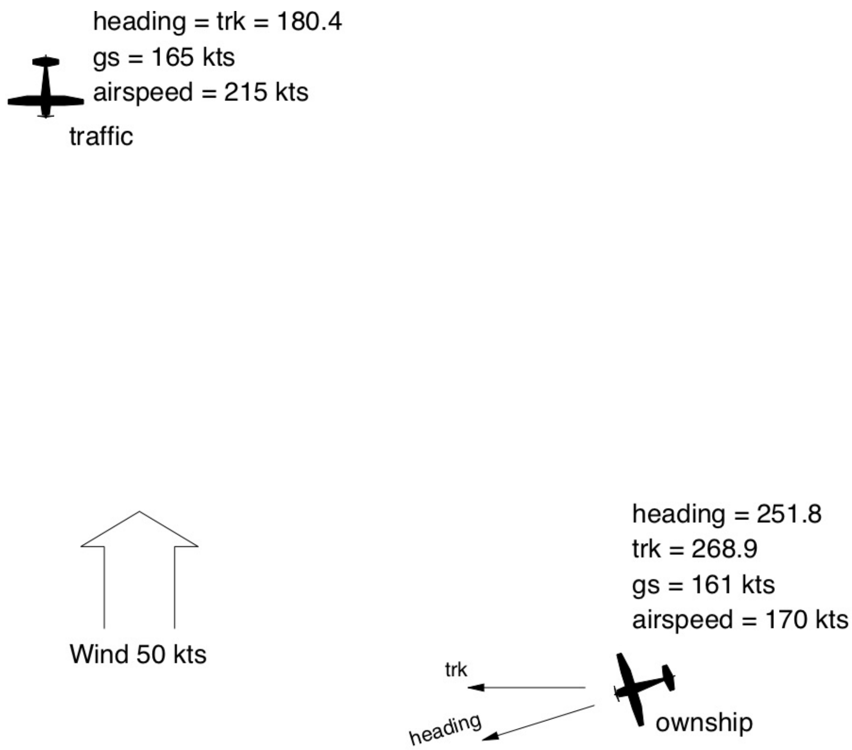


Figure 6-4. Example, Scenario 1b with random initial conditions added

The ownship's track is 268.9 degrees and, due to the south wind, its heading is 251.8 degrees. This represents a crab angle of 17.1 degrees into the wind. Figure 6-5 shows the heading resolution that DAIDALUS produces for this scenario and state.

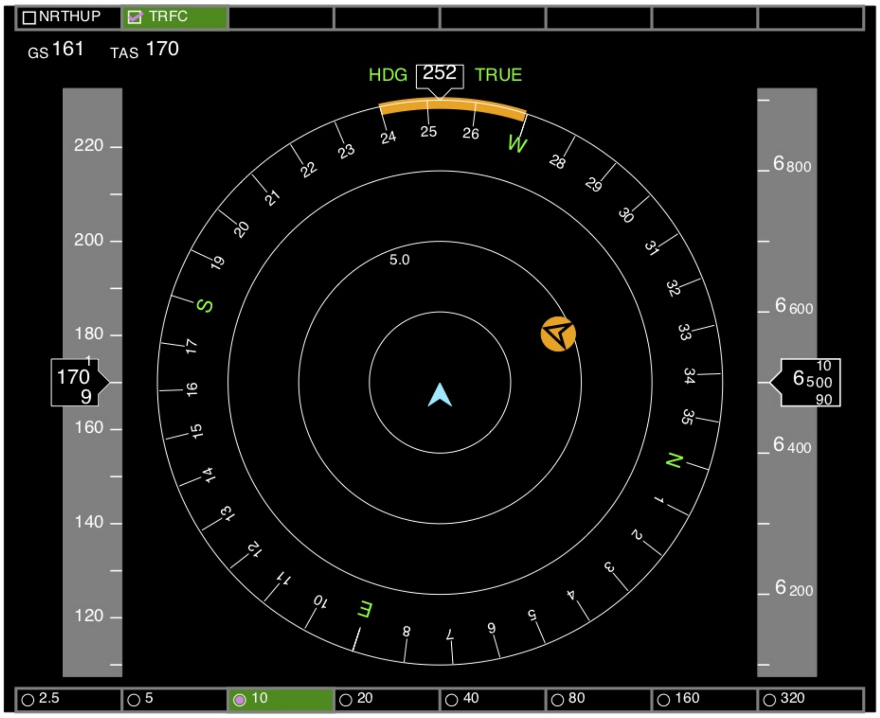


Figure 6-5. DAIDALUS heading resolution for the example scenario

Figure 6-5 shows the ownship in blue in the middle with the traffic aircraft in black inside an orange disk. The screen shows the two aircraft with a difference in heading of approximately 73 degrees. The traffic aircraft is shown with a bearing of approximately 62 degrees from the ownship. This is the angle where the pilot of the ownship will see the traffic aircraft (assuming that she/he can sees it at the distance of 4.8 nautical miles) with reference to its own aircraft's longitudinal axis.

The top of the display shows the conflict band in orange. The current ownship heading is 252 degrees. The heading guidance to avoid the conflict is to turn right 18 degrees heading 270 degrees, or to turn left 12 degrees heading 240 degrees. However, if the pilot chooses to turn left to remain well clear and starts implementing the resolution guidance, the guidance band will disappear from the traffic display. The pilot might stop the turn interpreting that the absence of conflict bands means clear of conflict within the alerting configuration (which is the correct interpretation). These will result in the conflict bands re-appearing a few seconds later with a larger turn to the left needed to remain well clear. This iteration will repeat several times and will result in a 67 degree turn to the left required to remain well clear.

Table 6-10 shows the initial guidance, the actual turn needed to remain well clear when the bands appear and disappear, the resulting tracks and ground speeds, and the deviation from course before the ownship can resume navigation.

Table 6-10. Initial guidance and actual maneuver required to stay well clear

Right Resolution Maneuver		Left Resolution Maneuver	
Initial Resolution Guidance	Actual Maneuver Required	Initial Resolution Guidance	Actual Maneuver Required
Turn 18 deg.	Turn 18 deg.	Turn 12 deg.	Turn 67 deg.
Heading 270	Heading 270	Heading 240	Heading 185
Track turn 17.4 deg.	Track turn 17.4 deg.	Track turn 12.4 deg.	Track turn 82.1 deg.
Track 286.2 deg.	Track 286.2 deg.	Track 256.4 deg.	Track 186.8 deg.
Ground speed 176.9	Ground speed 176.9 knots	Ground speed 151.1 knots	Ground speed 120.2 knots
	Deviation 1.16 NM		Deviation 7.88 NM

The data in Table 6-10 shows that if the pilot chooses to turn right, the initial guidance of 18 degrees right will be implemented and will be sufficient to stay well clear. This maneuver results in a course deviation of 1.16 nautical miles before the ownship can resume navigation. If the pilot chooses the left turn, the initial resolution guidance to turn left 12 degrees will likely not be sufficient and result in an actual turn of 67 degrees to a 185 heading. This results in a deviation of 7.88 nautical miles before the ownship can resume navigation.

Figure 6-6 shows the state of the aircraft resulting from the right turn when the ownship can resume navigation.

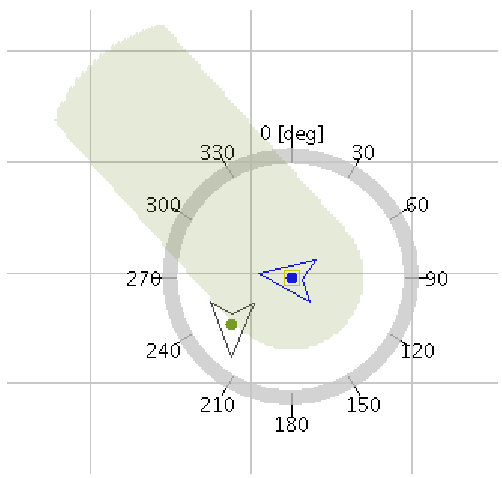


Figure 6-6. Right turn, clear of conflict, ownship resumes navigation

Figure 6-7 shows the state of the aircraft resulting from the left turn when the ownship can resume navigation.

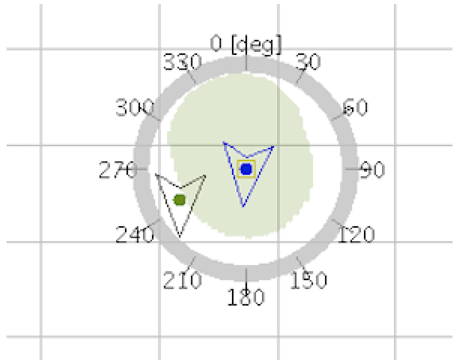


Figure 6-7. Left turn, clear of conflict, ownship resumes navigation

In the left turn maneuver, the ownship initially will intend to cross in front of the traffic aircraft. As the ownship turns left and the guidance fluctuates (and its ground speed decreases), it is unable to pass in front. The ownship continues to turn left to remain well clear, establishing an almost parallel track with the traffic aircraft. Because the ownship has lost ground speed, the traffic aircraft will pull away from the ownship, eventually allowing the ownship to resume navigation.

To address the issues presented in this sub-section, a "wrapper" has been added to the DAIDALUS logic. The wrapper is described in the next section.

7 Wrapper

Several approaches were formulated to address the intermittent guidance issue described in the previous sub-section. The objective was to add persistence to the guidance produced by DAIDALUS. Three potential solutions were explored:

- Utilize peripheral bands with longer look ahead time as way to maintain the conflict guidance.
- Maintain the initial bands when conflict is first detected, by a user defined time, and combine initial bands with potentially new generated conflict bands in a logically disjunctive combination.
- Dynamically adjust the alerting time parameter of the DAIDALUS detector and alerting functions using time to Closest Point of Approach.

After experiments and simulations with the three alternatives, it was found that the third alternative was the least complex and had the best performance and results.

7.1 Wrapper description

The wrapper works by dynamically adjusting the alerting time of the detector and alerting functions of the DAIDALUS algorithm. The alerting time is adjusted using the nominal alerting time parameter and the time to Closest Point of Approach. The nominal alerting time parameter is the parameter specified in the configuration file as “alerting_time” and has a value of 40 seconds for parameter sets 1 to 3. Figure 7-1 shows the information flow between the DAIDALUS algorithm and the wrapper.

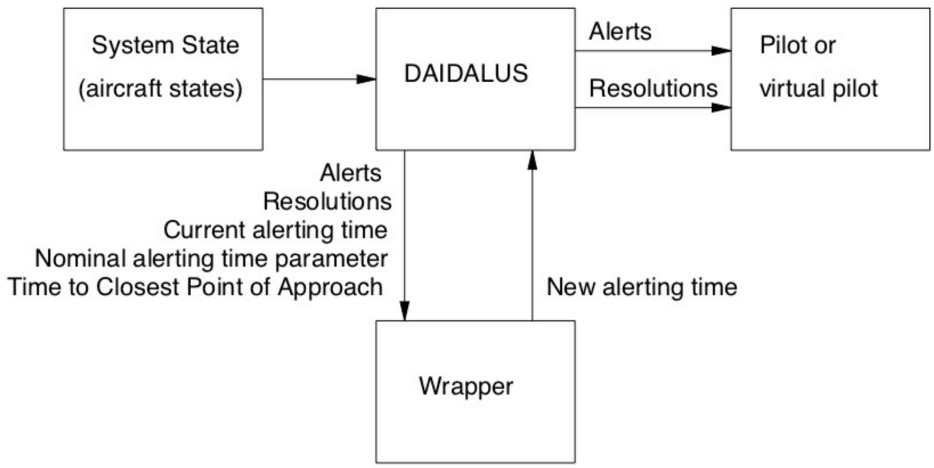


Figure 7-1. Information flow between DAIDALUS and wrapper

The wrapper uses the information provided by the DAIDALUS module and generates a new alerting time to be used by DAIDALUS in the next time iteration. Figure 7-2 shows the wrapper logic. In figure 7-2, the following abbreviations are used:

- Nominal – Nominal alerting time parameter specified in the configuration file
- Current – Alerting time currently being used by DAIDALUS in this time step
- New – New alerting time provided by the wrapper to be used by DAIDALUS in the next time step
- time2CPA – time to the Closest Point of Approach

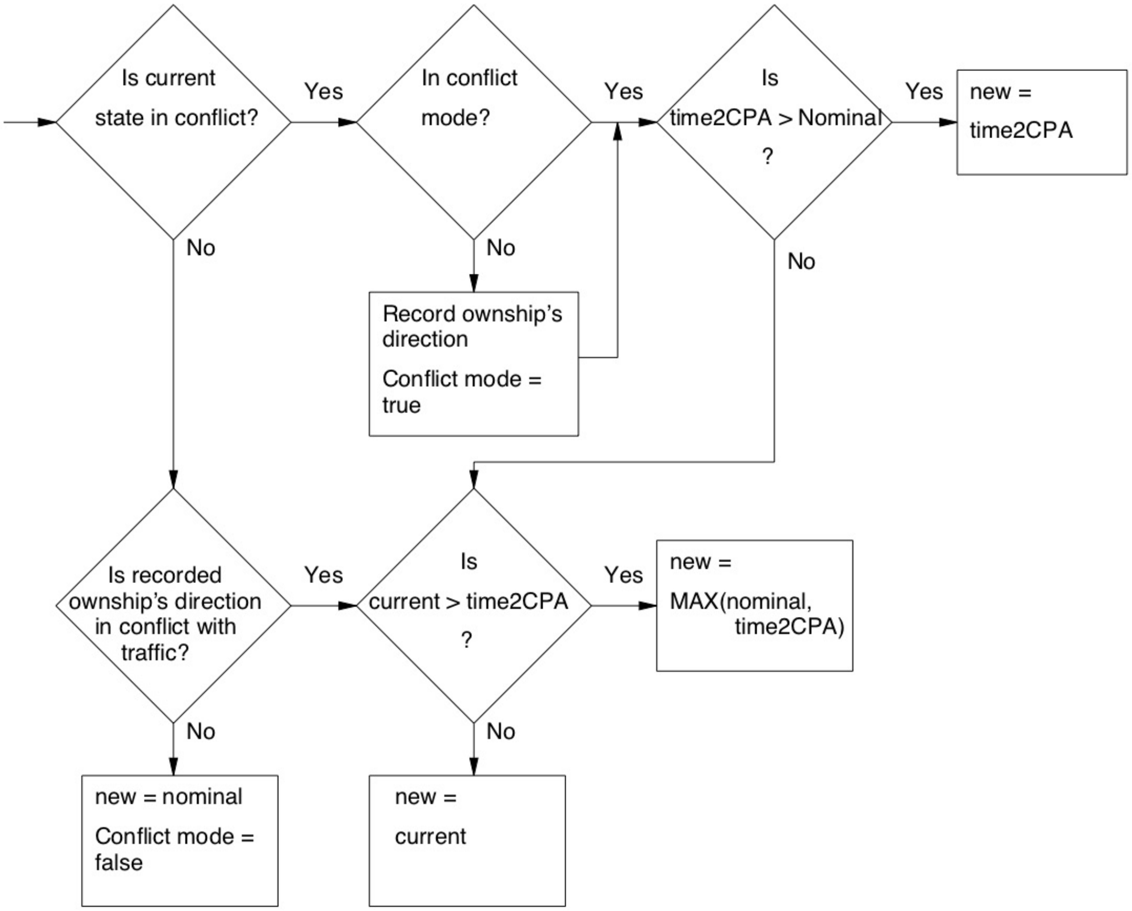


Figure 7-2. Wrapper logic

7.2 Simulation Results with Wrapper and DAIDALUS version 2.0.2b

Simulations were performed to determine the safety effect of the wrapper. Simulations were performed for the scenarios presented in sub-section 6.1 both with and without wind. The wind used in these simulations was from a random direction with a 50-knot magnitude. Also, for scenario 1, the simulations were performed for winds from the north, south, north-west and south-east. Table 7-1 shows the results for scenarios 1 to 1e with the wind conditions.

Table 7-1. Simulation results, scenario 1 to 1e, DAIDALUS version 2.0.2b with wrapper, 5 seconds average delay

		Severity, SMS					
Scenario	Wind out of (vector)	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic

1	No wind (0,0,0)	95.74%	4.26%	0	0	0	0
1a	North (0,-50,0)	95.55%	4.45%	0	0	0	0
1b	South (0,50,0)	95.81%	4.19%	0	0	0	0
1c	North-west (35,-35,0)	95.12%	4.88%	0	0	0	0
1d	South-east (-35,35,0)	96.47%	3.53%	0	0	0	0
1e	50 knots random	95.77%	4.23%	0	0	0	0

Results in Table 7-1 shows that for scenarios 1 to 1e the wrapper, with version 2.0.2b of DIADALUS, reduces the instances of losses of well clear of severity Minimal in all wind conditions. This is in addition to solving the operational issues that were discussed in sub-section 6.7. The results also become more consistent from one wind scenario to the other.

8 DAIDALUS Version 2.0.2e

This section contains the simulation results using DAIDALUS version 2.0.2e. Table 8-1 shows the results comparing the severity of encounters when no resolution is implemented and scenarios with and without wind and with and without wrapper. The wind for the scenarios are winds of 50 knots magnitude from a random direction. Only horizontal direction resolution guidance are shown in the table.

Table 8-1. Severity, horizontal guidance, with and without wrapper and with and without wind, 5 seconds average delay

			Severity					
Scenario	Wind	Wrapper	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
1	No wind	No resolut.	0.04%	0.31%	2.26%	8.16%	86.44%	2.79%
	No wind	No wrapper	95.76%	4.24%	0	0	0	0
	Wind	No wrapper	95.16%	4.84%	0	0	0	0
	No wind	Wrapper.	95.74%	4.26%	0	0	0	0
	Wind	Wrapper	95.76%	4.24%	0	0	0	0
2	No wind	No resolut.	0.01%	0.35%	2.17%	7.15%	87.23%	3.09%
	No wind	No wrapper	95.80%	4.20%	0	0	0	0
	Wind	No wrapper	95.88%	4.12%	0	0	0	0
	No wind	Wrapper	95.77%	4.23%	0	0	0	0

	Wind	Wrapper	95.80%	4.20%	0	0	0	0
3	No wind	No resolut.	0	0.03%	0.78%	3.68%	91.8%	3.74%
	No wind	No wrapper.	96.10%	3.90%	0	0	0	0
	Wind	No wrapper	96.16%	3.84%	0	0	0	0
	No wind	Wrapper	96.10%	3.90%	0	0	0	0
	Wind	Wrapper	96.16%	3.84%	0	0	0	0
4	No wind	No resolut.	0	0	0.37%	2.88%	92.7%	4.05%
	No wind	No wrapper	95.88%	4.12%	0	0	0	0
	Wind	No wrapper	96.12%	3.88%	0	0	0	0
	No wind	Wrapper	96.00%	4.00%	0	0	0	0
	Wind	Wrapper	96.12%	3.88%	0	0	0	0
5	No wind	No resolut.	0	1.72%	44.6%	49.2%	4.48%	0
	No wind	No wrapper	14.60%	78.56%	5.48%	0.24%	1.12%	0
	Wind	No wrapper	24.96%	34.64%	9.80%	8.88%	21.72%	0
	No wind	Wrapper	15.92%	77.13%	5.66%	0.32%	0.97%	0
	Wind	Wrapper	25.00%	34.60%	9.80%	8.88%	21.72%	0
6	No wind	No resolut.	0.08%	1.08%	4.54%	11.7%	80.2%	2.37%
	No wind	No wrapper	99.96%	0.04%	0	0	0	0
	Wind	No wrapper	91.44%	8.56%	0	0	0	0
	No wind	Wrapper	98.00%	2.00%	0	0	0	0
	Wind	Wrapper	91.44%	8.56%	0	0	0	0
7	No wind	No resolut.	9.73%	36.9%	17.8%	12.6%	22.6%	0.31%
	No wind	No wrapper	100%	0	0	0	0	0
	Wind	No wrapper	100%	0	0	0	0	0
	No wind	Wrapper	100%	0	0	0	0	0
	Wind	Wrapper	100%	0	0	0	0	0
8a	No wind	No resolut.	0	0	0	0.11%	87.1%	12.8%
	No wind	No wrapper	0	0.32%	7.56%	21.68%	70.12%	0.32%
	Wind	No wrapper	12.8%	15.68%	16.68%	17.16%	48.48%	0.72%
	No wind	Wrapper	0	0.32%	7.56%	21.68%	70.12%	0.32%
	Wind	Wrapper	12.8%	15.68%	16.68%	17.16%	48.48%	0.72%
8b	No wind	No resolut.	0	0	0	0.11%	87.1%	12.8%
	No wind	No wrapper	0.08%	98.84%	1.00%	0	0.08%	0
	Wind	No wrapper	0.80%	97.44%	1.60%	0.12%	0.04%	0
	No wind	Wrapper	0.08%	98.84%	1.00%	0	0.08%	0

	Wind	Wrapper	0.80%	97.44%	1.60%	0.12%	0.04%	0

The data in table 8-1 shows that the wrapper, when used in conjunction with DAIDALUS 2.0.2e, has little effect on the severity of the encounters.

Table 8-2 shows a comparison of the severity of encounters when using DAIDALUS version 2.0.2b and version 2.0.2e with no wind and no wrapper.

Table 8-2. Severity, DAIDALUS versions 2.0.2b and 2.0.2e, no wind, no wrapper, 5 seconds average delay

		Severity					
Scenario	DAIDALUS version	No Loss of Well Clear	5 Minimal	4 Minor	3 Major	2 Hazardous	1 Catastrophic
1	2.0.2b	54.0%	46.0%	0	0	0	0
	2.0.2e	95.76%	4.24%	0	0	0	0
2	2.0.2b	76.4%	23.6%	0	0	0	0
	2.0.2e	95.80%	4.20%	0	0	0	0
3	2.0.2b	83.2%	16.8%	0	0	0	0
	2.0.2e	96.10%	3.90%	0	0	0	0
4	2.0.2b	83.6%	16.4%	0	0	0	0
	2.0.2e	95.88%	4.12%	0	0	0	0
5	2.0.2b	9.47%	31.8%	56.8%	0.99%	0.92%	0
	2.0.2e	14.60%	78.56%	5.48%	0.24%	1.12%	0
6	2.0.2b	43.9%	56.1%	0	0	0	0
	2.0.2e	99.96	0.04%	0	0	0	0
7	2.0.2b	92.3%	7.7%	0	0	0	0
	2.0.2e	100%	0	0	0	0	0
8a	2.0.2b	0	0.01%	0.98%	8.39%	90.62%	0
	2.0.2e	0	0.32%	7.56%	21.68%	70.12%	0.32%
8b	2.0.2b	0	79.9%	16.6%	2.72%	0.79%	0
	2.0.2e	0.08%	98.84%	1.00%	0	0.08%	0

For scenarios 1 through 4 and scenarios 6, 7, and 8b, the newer version of DAIDALUS lowers the severity of the encounters. For scenario 5, the newer version increases the percentage of Hazardous encounters by a very small amount (from 0.92 percent to 1.12 percent). For scenario 8a, the newer version decreases encounters of severity Hazardous from 90.62 percent to 70.12 percent but increases the

Catastrophic encounters from 0 to 0.32 percent. Scenarios 5, 8a and 8b are the most challenging scenarios for the detect and avoid logic and involve turns by the ownship or the traffic aircraft.

9 Summary and Conclusion

In this document, the DANTi concept is evaluated to determine its effectiveness in staying well clear of traffic aircraft and reducing the risk of collisions. Flight test data as well as simulations have been analyzed in terms of severity of encounters to determine the effectiveness of the DANTi concept and the underlying DAIDALUS detect and avoid algorithm

The analysis of the flight test data shows that the flight crew can effectively implement the guidance provided by DANTi. When the guidance was implemented, the two aircraft remained mostly well clear, and even if there was a small infringement into the protected volume, risk of collision was virtually eliminated. The data also shows that when the guidance was not implemented, the aircraft passed dangerously close on the horizontal dimension.

To further evaluate DANTi and DAIDALUS, additional scenarios were developed beyond the flight test scenarios. The additional scenarios included climb and descent scenarios and turn scenarios. Analysis of simulation data shows a significant reduction in encounter severity and reduction of collision risk. For the simulation runs and analysis, two versions of DAIDALUS were used: version 2.0.2b and version 2.0.2e. Simulations using DAIDALUS version 2.0.2e showed an improvement in severity in most cases over the previous version.

During the analysis of simulation data, it was observed that a large deviation occurred in some cases when following the guidance. Further analysis showed that in some scenarios, the guidance was intermittent, appearing and disappearing as the maneuver was implemented. These characteristics were deemed to be operationally undesirable. To address these issues, a wrapper was developed in which the alerting time of the DAIDALUS algorithm was dynamically adjusted. Using the wrapper in conjunction with DAIDALUS version 2.0.2b resulted in improvements including reduction in severity of the encounters and elimination of the intermittent guidance and large deviation issues. Using the wrapper with DAIDALUS version 2.0.2e addressed the intermittent and large deviation issues, but had no effect on the severity of the encounters.

The analysis of the flight test data and the analysis of the simulation data suggest that the DANTi concept and the underlying DAIDALUS algorithm have the potential to significantly reduce the severity of encounters and the risk of collision as compared with aircraft employing see and avoid as the only means to stay well clear of other aircraft.

10 References

[1] Muñoz, Narkawicz, Hagen, Upchurch, Dutle, Consiglio, Chamberlain, “DAIDALUS: Detect and Avoid Alerting Logic for Unmanned Systems,” Proceedings of the 34th Digital Avionics Systems Conference (DASC 2015), Prague, Czech Republic, 2015.

[2] RTCA, “Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems,” RTCA DO-365, May 2017.

[3] Chamberlain, Consiglio, Muñoz, "DANTi Detect and Avoid iN The Cockpit," Proceedings of the 17th AIAA Aviation Technology, Integration, and Operations Conference (ATIO 2017), Denver, CO, AIAA-2017-4491, June 2017.
[4] NASA Langley Formal Methods Team, "DAIDALUS Reference Manual," internal document.
[5] FAA, ATO, Safety Management System Manual, July 2017.
[6] Fernandez Guasti, M. "Analytic Geometry of Some Rectilinear Figures." International Journal of Mathematical Education in Science and Technology, volume 23, no 6, 895-913, 1992.
[7] National Transportation Safety Board, Accident number WPR15MA243B, Factual report 31 October 2016, Final report 15 November 2016.

Appendix A Data file example

This appendix contains an example of the data contained in the flight test data files recorded during the DANTi flight tests (file daidalus_071817.123243.txt). It is a one second time step of the data. The first part is the configuration parameters for the DAIDALUS detect and avoid algorithm. The second part is the state of the aircraft. The third part are the calculations produced by DAIDALUS.

```
Daidalus Object
# V-1.0.1
# Bands Parameters
lookahead_time = 180.000000 [s]
left_trk = 180.000000 [deg]
right_trk = 180.000000 [deg]
min_gs = 10.000000 [knot]
max_gs = 700.000000 [knot]
min_vs = -6000.000000 [fpm]
max_vs = 6000.000000 [fpm]
min_alt = 100.000000 [ft]
max_alt = 50000.000000 [ft]
# Kinematic Parameters
trk_step = 1.000000 [deg]
gs_step = 5.000000 [knot]
vs_step = 100.000000 [fpm]
alt_step = 100.000000 [ft]
horizontal_accel = 2.000000 [m/s^2]
vertical_accel = 0.250000 [G]
turn_rate = 3.000000 [deg/s]
bank_angle = 0.000000 [deg]
vertical_rate = 500.000000 [fpm]
# Recovery Bands Parameters
recovery_stability_time = 2.000000 [s]
min_horizontal_recovery = 4000.000000 [ft]
min_vertical_recovery = 1000.000000 [ft]
recovery_trk = true
recovery_gs = false
recovery_vs = true
recovery_alt = true
# Collision Avoidance Bands Parameters
ca_bands = true
ca_factor = 0.200000
horizontal_nmac = 500.000000 [ft]
vertical_nmac = 100.000000 [ft]
# Implicit Coordination Parameters
conflict_crit = false
recovery_crit = false
# Horizontal Contour Threshold
contour_thr = 180.000000 [deg]
# Alert Levels
alert_1_alerting_time = 40.000000 [s]
alert_1_detector = det_1
alert_1_early_alerting_time = 55.000000 [s]
alert_1_region = NEAR
alert_1_spread_alt = 0.000000 [ft]
alert_1_spread_gs = 0.000000 [knot]
alert_1_spread_trk = 0.000000 [deg]
alert_1_spread_vs = 0.000000 [fpm]
conflict_level = 1
det_1_WCV_DTHR = 4000.000000 [ft]
det_1_WCV_TCOA = 0.000000 [s]
det_1_WCV_TTHR = 35.000000 [s]
det_1_WCV_ZTHR = 1000.000000 [ft]
load_core_detection_det_1 = gov.nasa.larcfm.ACCoRD.WCV_TAUMOD
###
```

```
Aircraft States:
NAME lat lon alt trk gs vs time
[none] [deg] [deg] [ft] [deg] [knot] [fpm] [s]
ownship, 37.01317549, -76.98933363, 6325.000000, 299.968868, 98.495193, 128.000007, 47403.495566
ad8db3, 38.21684360, -77.89596310, 7800.000000, 340.153531, 156.929134, 0.000000, 47403.495566
a9dde9, 37.50350470, -76.73956630, 2425.000000, 61.488791, 127.501717, 1216.000000, 47403.495566
a66420, 37.12260960, -75.99749560, 975.000000, 188.361021, 95.510788, -832.000000, 47403.495566
a692ea, 37.20438480, -76.06227630, 2500.000000, 180.026644, 116.902606, -256.000000, 47403.495566
a5f6b3, 37.56701940, -76.63993830, 4500.000000, 263.783967, 96.912461, 768.000000, 47403.495566
a9b688, 37.16977350, -76.41248700, 1025.000000, 237.554281, 142.475174, -768.000000, 47403.495566
a9d528, 35.94561330, -77.80830860, 4800.000000, 359.822041, 136.021864, 128.000000, 47403.495566
c07190, 36.97071070, -77.76811830, 10750.000000, 36.678037, 209.362561, 0.000000, 47403.495566
a6be69, 36.63603540, -76.38678070, 7400.000000, 309.488465, 114.048445, 0.000000, 47403.495566
a4dba2, 36.51544330, -77.87879700, 7850.000000, 213.273630, 168.699333, 0.000000, 47403.495566
a46e28, 37.51077890, -77.32613320, 0.000000, 193.091630, 34.269736, 128.000000, 47403.495566
aa3fdf, 36.59442900, -76.12836590, 2375.000000, 236.312625, 111.471693, -2880.000000,47403.495566
a12748, 36.29949330, -77.47852560, 3800.000000, 239.228954, 101.482283, -64.000000, 47403.495566
acf045, 37.14807980, -75.85696930, 2225.000000, 269.593379, 114.101583, 128.000000, 47403.495566
a69cae, 37.08585260, -76.37759680, -175.000000, 54.272265, 3.530477, 0.000000, 47403.495566
a63ed4, 37.01120130, -77.00315230, 6825.000000, 181.550910, 146.835135, 64.000000, 47403.495566
Time: 47403.495566 [s]
NAME lat lon alt trk gs vs time
[none] [deg] [deg] [ft] [deg] [knot] [fpm] [s]
ownship, 37.01317549, -76.98933363, 6325.000000, 299.968868, 98.495193, 128.000007, 47403.495566
ad8db3, 38.21684360, -77.89596310, 7800.000000, 340.153531, 156.929134, 0.000000, 47403.495566
a9dde9, 37.50350470, -76.73956630, 2425.000000, 61.488791, 127.501717, 1216.000000, 47403.495566
a66420, 37.12260960, -75.99749560, 975.000000, 188.361021, 95.510788, -832.000000, 47403.495566
a692ea, 37.20438480, -76.06227630, 2500.000000, 180.026644, 116.902606, -256.000000, 47403.495566
a5f6b3, 37.56701940, -76.63993830, 4500.000000, 263.783967, 96.912461, 768.000000, 47403.495566
a9b688, 37.16977350, -76.41248700, 1025.000000, 237.554281, 142.475174, -768.000000, 47403.495566
a9d528, 35.94561330, -77.80830860, 4800.000000, 359.822041, 136.021864, 128.000000, 47403.495566
c07190, 36.97071070, -77.76811830, 10750.000000, 36.678037, 209.362561, 0.000000, 47403.495566
a6be69, 36.63603540, -76.38678070, 7400.000000, 309.488465, 114.048445, 0.000000, 47403.495566
a4dba2, 36.51544330, -77.87879700, 7850.000000, 213.273630, 168.699333, 0.000000, 47403.495566
a46e28, 37.51077890, -77.32613320, 0.000000, 193.091630, 34.269736, 128.000000, 47403.495566
aa3fdf, 36.59442900, -76.12836590, 2375.000000, 236.312625, 111.471693, -2880.000000,47403.495566
a12748, 36.29949330, -77.47852560, 3800.000000, 239.228954, 101.482283, -64.000000, 47403.495566
acf045, 37.14807980, -75.85696930, 2225.000000, 269.593379, 114.101583, 128.000000, 47403.495566
a69cae, 37.08585260, -76.37759680, -175.000000, 54.272265, 3.530477, 0.000000, 47403.495566
a63ed4, 37.01120130, -77.00315230, 6825.000000, 181.550910, 146.835135, 64.000000, 47403.495566
Conflict Criteria: Disabled
Recovery Criteria: Disabled
Most Urgent Aircraft: _NoAc_
Horizontal Epsilon: 0
Vertical Epsilon: 0
Conflict Aircraft (alert level 1): {a63ed4}
Ownship Track: 299.968868 [deg]
Region of Current Track: NEAR
Track Bands [deg,deg]:
  [0.000000, 119.968868] RECOVERY
  [119.968868, 301.968868] NEAR
  [301.968868, 360.000000] RECOVERY
Peripheral Track Aircraft (alert level 1): {}
Track Resolution (right): 301.968868 [deg]
Track Resolution (left): 119.968868 [deg]
Preferred Track Direction: right
Time to Track Recovery: 2.429688 [s]
Ownship Ground Speed: 98.495193 [knot]
Region of Current Ground Speed: NEAR
Ground Speed Bands [knot,knot]:
  [10.000000, 700.000000] NEAR
Peripheral Ground Speed Aircraft (alert level 1): {}
Ground Speed Resolution (up): infty [knot]
Ground Speed Resolution (down): -infty [knot]
Preferred Ground Speed Direction: down
Time to Ground Speed Recovery: NaN [s]
Ownship Vertical Speed: 128.000007 [fpm]
```

```
Region of Current Vertical Speed: RECOVERY
Vertical Speed Bands [fpm,fpm]:
  [-6000.000000, 6000.000000] RECOVERY
Peripheral Vertical Speed Aircraft (alert level 1): {}
Vertical Speed Resolution (up): NaN [fpm]
Vertical Speed Resolution (down): NaN [fpm]
Preferred Vertical Speed Direction: down
Time to Vertical Speed Recovery: 5.437500 [s]
Ownship Altitude: 6325.000000 [ft]
Region of Current Altitude: RECOVERY
Altitude Bands [ft,ft]:
  [100.000000, 50000.000000] RECOVERY
Peripheral Altitude Aircraft (alert level 1): {}
Altitude Resolution (up): NaN [ft]
Altitude Resolution (down): NaN [ft]
Preferred Altitude Direction: down
Time to Altitude Recovery: 5.437500 [s]
Last Times to Maneuver with Respect to ad8db3
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a9dde9
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a66420
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a692ea
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a5f6b3
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a9b688
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a9d528
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to c07190
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a6be69
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a4dba2
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
```

```
Last Times to Maneuver with Respect to a46e28
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to aa3fdf
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a12748
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to acf045
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a69cae
  Last Time to Track Maneuver: NaN [s]
  Last Time to Ground Speed Maneuver: NaN [s]
  Last Time to Vertical Speed Maneuver: NaN [s]
  Last Time to Altitude Maneuver: NaN [s]
Last Times to Maneuver with Respect to a63ed4
  Last Time to Track Maneuver: -infty [s]
  Last Time to Ground Speed Maneuver: -infty [s]
  Last Time to Vertical Speed Maneuver: -infty [s]
  Last Time to Altitude Maneuver: -infty [s]
```

Appendix B. Configuration File

This appendix contains the DAIDALUS configuration file used in the simulation runs.

```
# Daidalus Object
# V-2.0.2b
# Bands Parameters
lookahead_time = 180.000000 [s]
left_hdir = 180.000000 [deg]
right_hdir = 180.000000 [deg]
min_hs = 60.000000 [knot]
max_hs = 250.000000 [knot]
min_vs = -6000.000000 [fpm]
max_vs = 6000.000000 [fpm]
min_alt = 100.000000 [ft]
max_alt = 50000.000000 [ft]
# Relative Bands Parameters
below_relative_hs = 0.000000 [knot]
above_relative_hs = 0.000000 [knot]
below_relative_vs = 0.000000 [fpm]
above_relative_vs = 0.000000 [fpm]
below_relative_alt = 0.000000 [ft]
above_relative_alt = 0.000000 [ft]
# Kinematic Parameters
step_hdir = 1.000000 [deg]
step_hs = 5.000000 [knot]
step_vs = 100.000000 [fpm]
step_alt = 100.000000 [ft]
horizontal_accel = 2.000000 [m/s^2]
vertical_accel = 0.250000 [G]
turn_rate = 3.000000 [deg/s]
bank_angle = 0.000000 [deg]
vertical_rate = 500.000000 [fpm]
# Recovery Bands Parameters
min_horizontal_recovery = 4000.0 [ft]
min_vertical_recovery = 450.000000 [ft]
recovery_hdir = true
recovery_hs = true
recovery_vs = true
recovery_alt = true
# Collision Avoidance Bands Parameters
ca_bands = true
ca_factor = 0.100000
horizontal_nmac = 500.000000 [ft]
vertical_nmac = 100.000000 [ft]
# Hysteresis and stability parameters
recovery_stability_time = 3.000000 [s]
resolution_hysteresis_time = 5.000000 [s]
max_delta_resolution_hdir = 10.000000 [deg]
max_delta_resolution_hs = 10.000000 [knot]
max_delta_resolution_vs = 100.000000 [fpm]
max_delta_resolution_alt = 100.000000 [ft]
# Implicit Coordination Parameters
conflict_crit = false
recovery_crit = false
# Sensor Uncertainty Mitigation Parameters
h_pos_z_score = 0.000000
h_vel_z_score_min = 0.000000
```

```
h_vel_z_score_max = 0.000000
h_vel_z_distance = 0.000000 [nmi]
v_pos_z_score = 0.000000
v_vel_z_score = 0.000000
# Horizontal Contour Threshold
contour_thr = 180.000000 [deg]
# Alerting Logic
ownship_centric_alerting = true
corrective_region = NEAR
alerters = Buffered_DWC_Phase_I
Buffered_DWC_Phase_I_alert_1_alerting_time = 40.000000 [s]
Buffered_DWC_Phase_I_alert_1_detector = det_1
Buffered_DWC_Phase_I_alert_1_early_alerting_time = 180.000000 [s]
Buffered_DWC_Phase_I_alert_1_region = NEAR
Buffered_DWC_Phase_I_alert_1_spread_alt = 0.000000 [ft]
Buffered_DWC_Phase_I_alert_1_spread_hdir = 0.000000 [deg]
Buffered_DWC_Phase_I_alert_1_spread_hs = 0.000000 [knot]
Buffered_DWC_Phase_I_alert_1_spread_vs = 0.000000 [fpm]
conflict_level = 1
Buffered_DWC_Phase_I_det_1_WCV_DTHR = 4000.0 [ft]
Buffered_DWC_Phase_I_det_1_WCV_TCOA = 20.000000 [s]
Buffered_DWC_Phase_I_det_1_WCV_TTHR = 35.000000 [s]
Buffered_DWC_Phase_I_det_1_WCV_ZTHR = 450.000000 [ft]
Buffered_DWC_Phase_I_load_core_detection_det_1 = gov.nasa.larcfm.ACCoRD.WCV_TAUMOD
```

Appendix C. Low Altitude Wind Characterization over the Continental United States

1 Introduction

This paper presents low altitude wind data, from 6,000 feet to 18,000 feet above mean sea level (MSL), over the continental United States. The data covers 16 days sampling in the time span from the 4th of February 2019 to the 8th of March 2019. The data was obtained from the Aviation Weather Center, National Oceanic and Atmospheric Administration (NOAA), National Weather Service.

The wind and temperature data are issued every 6 hours through the day. The projections are made to 6, 12, and 24 hours. The data presented in this paper are 6 hour projections.

2 Data

The sampling days for the wind data are shown in table 2-1 with valid times in Eastern standard, Pacific standard, and universal time coordinated (Zulu) times.

Table 2-1. Sample days for wind data

Sample	Day	Easter Standard time	Pacific Standard time	Universal Time Coordinated
1	2019-02-04	1:00 PM	10:00 AM	18:00 Z
2	2019-02-05	1:00 PM	10:00 AM	18:00 Z
3	2019-02-06	7:00 AM	4:00 AM	12:00 Z
4	2019-02-07	7:00 PM	4:00 PM	24:00 Z
5	2019-02-08	7:00 PM	4:00 PM	24:00 Z
6	2019-02-09	7:00 PM	4:00 PM	24:00 Z
7	2019-02-10	7:00 PM	4:00 PM	24:00 Z
8	2019-02-11	7:00 AM	4:00 AM	12:00 Z
9	2019-02-13	7:00 AM	4:00 AM	12:00 Z
10	2019-02-14	7:00 AM	4:00 AM	12:00 Z
11	2019-02-18	1:00 PM	10:00 AM	18:00 Z
12	2019-02-22	1:00 PM	10:00 AM	18:00 Z
13	2019-02-24	7:00 AM	4:00 AM	12:00 Z
14	2019-02-26	7:00 PM	4:00 PM	24:00 Z
15	2019-03-04	1:00 PM	10:00 AM	18:00 Z
16	2019-03-08	7:00 AM	4:00 AM	12:00 Z

The locations of the weather data, represented by the 3 letter IATA (International Air Transport Association) airport identifier, are shown in Figure 2-1.

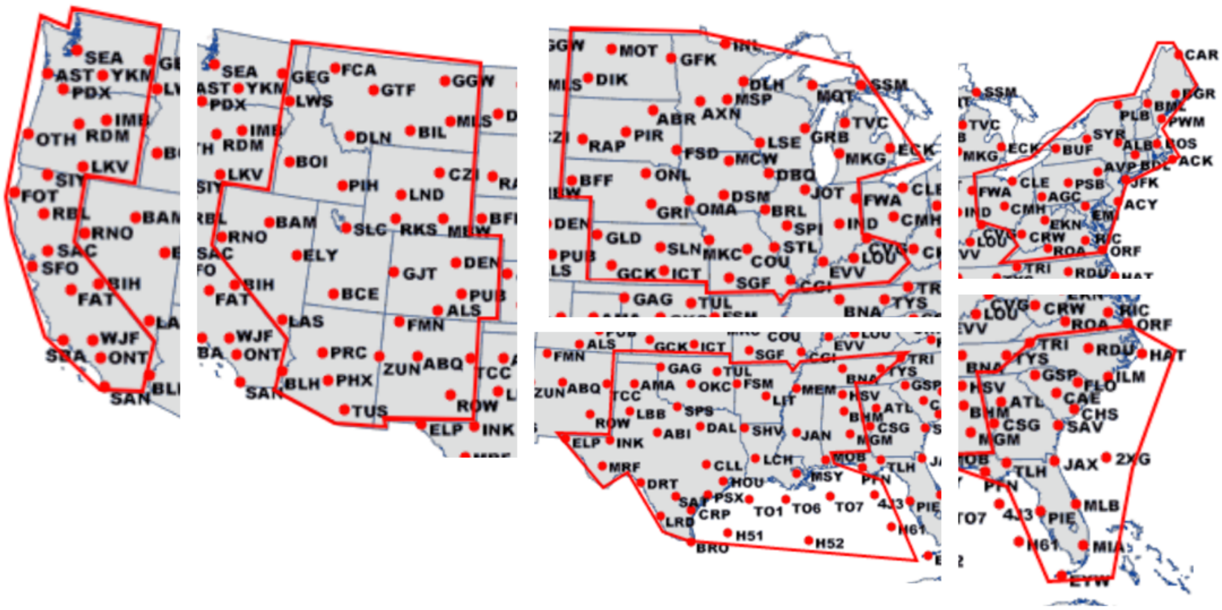


Figure 2-1. Winds and Temperatures data locations

The data are divided in the following regions:

- North-east
- South-east
- North-central
- South-central
- Mountain
- Pacific

There are 25 locations in the north-east, 18 locations in the south-east, 41 locations in the north-central, 40 locations in the south-central, 31 locations in the mountain region, and 21 locations in the Pacific region. The data comprises a total of 176 locations over the continental United States.

Tables 2-2 through 2-7 contain the average, minimum, and maximum winds at 6,000, 12,000, and 18,000 feet above Mean Sea Level (MSL) for the days shown in Table 2-1 and locations shown in Figure 2-1.

Table 2-2. North-east, Average, Minimum, and Maximum winds, knots

Location	Altitude, MSL								
	6,000 ft.			12,000 ft.			18,000 ft.		
	Avg.	Min.	Max.	Avg.	Min.	Max	Avg.	Min.	Max.
BDL	27.75	13	50	52.44	25	86	70.00	30	117
BGR	34.75	14	66	47.44	25	74	69.63	39	112
CAR	33.00	5	63	47.69	25	71	57.00	13	99
PWM	31.50	13	56	48.63	24	88	72.25	42	129
EMI	31.50	0	58	48.50	9	97	69.00	7	132

ACK	30.63	8	54	54.75	19	93	68.56	34	116
BOS	29.19	7	50	54.38	21	92	70.63	39	116
BML	34.31	9	56	49.19	29	78	67.25	33	115
ACY	33.75	0	56	50.50	13	80	68.56	9	134
ALB	28.19	13	48	50.75	28	84	70.81	35	120
BUF	27.63	10	46	43.13	20	69	60.44	28	92
JFK	30.13	5	56	53.06	14	88	69.25	23	121
PLB	31.25	9	53	46.94	19	75	64.19	17	115
SYR	28.50	11	51	46.88	26	76	67.13	33	108
CLE	27.81	10	53	44.00	14	71	60.63	20	114
CMH	30.25	9	54	44.81	18	71	66.50	16	116
CVG	29.38	8	55	44.06	8	72	65.88	21	107
AGC	30.13	10	56	44.63	15	81	67.88	14	109
AVP	28.69	9	55	50.88	23	92	69.38	20	120
PSB	30.38	10	58	46.13	23	84	68.56	16	116
ORF	28.56	12	49	44.50	13	86	62.06	18	117
RIC	27.94	10	62	45.38	6	78	62.63	13	119
ROA	30.00	0	67	47.56	13	93	63.31	7	116
CRW	27.19	0	56	48.00	10	85	70.13	12	125
EKN	29.38	0	56	49.19	10	78	71.81	8	130

Table 2-3. South-east Average, Minimum, and Maximum winds, knots

Location	Altitude, MSL								
	6,000 ft.			12,000 ft.			18,000 ft.		
	Avg.	Min.	Max.	Avg.	Min.	Max	Avg.	Min.	Max.
EYW	11.31	5	19	12.69	7	24	18.94	5	31
JAX	14.38	0	39	24.81	8	49	35.88	14	63
MIA	10.19	0	16	13.50	0	28	25.44	5	100
MLB	14.44	6	30	18.31	0	35	22.94	5	43
PFN	16.13	0	37	22.44	5	52	38.00	19	71
PIE	12.69	0	30	18.69	5	38	23.69	7	47
TLH	16.00	0	41	22.63	5	51	38.50	15	70
ATL	24.75	11	56	36.06	21	69	52.06	25	86
CSG	21.25	6	46	31.50	13	59	47.44	24	73
SAV	18.81	0	44	26.75	14	52	43.56	13	73
HAT	25.25	8	55	39.19	17	73	55.25	14	88
ILM	23.56	7	47	34.63	19	61	51.31	18	80
RDU	26.00	9	56	39.56	8	84	58.19	9	104
CAE	23.31	6	50	33.13	17	62	50.06	17	80
CHS	20.81	7	46	28.56	15	50	45.19	14	73
FLO	23.81	8	49	34.25	17	62	51.38	18	81
GSP	26.88	8	63	39.50	16	74	56.88	21	96
2XG	12.13	0	32	24.69	0	46	32.88	16	55

Table 2-4. North-central Average, Minimum, and Maximum winds, knots

Location	Altitude, MSL								
	6,000 ft.			12,000 ft.			18,000 ft.		
	Avg.	Min.	Max.	Avg.	Min.	Max	Avg.	Min.	Max.
BRL	27.31	5	59	40.63	23	71	57.81	33	126
DBQ	24.88	0	54	40.13	12	63	55.38	25	81
DSM	27.13	0	60	38.81	19	53	50.13	30	64
MCW	24.50	0	57	38.56	7	56	50.56	15	70
JOT	26.00	0	53	40.94	15	73	58.38	26	120
SPI	28.38	5	61	45.38	19	95	61.19	44	121
EVV	29.56	9	55	47.63	8	84	68.06	37	113
FWA	29.63	9	58	44.38	22	78	62.56	32	105
IND	28.31	7	55	45.63	16	81	63.06	39	112
GCK	22.50	10	47	32.94	16	51	51.50	34	77
GLD	21.13	0	39	31.25	20	49	48.81	23	73
ICT	24.63	0	42	38.75	27	53	52.06	32	79
SLN	24.19	6	41	35.50	25	49	48.88	34	68
LOU	30.31	7	60	46.56	5	86	69.63	36	118
ECK	27.31	5	54	42.13	18	67	56.44	26	86
MKG	27.19	5	53	42.69	14	66	55.94	21	104
MQT	16.25	0	42	32.75	14	58	45.63	15	77
SSM	23.75	0	62	35.31	14	59	48.13	21	85
TVC	22.75	0	56	37.94	19	55	53.13	24	88
AXN	19.13	0	42	32.81	13	57	43.19	6	74
DLH	16.63	0	34	29.19	6	50	42.69	10	77
INL	15.94	0	29	24.25	0	46	39.38	10	79
MSP	22.56	5	44	34.50	12	58	46.31	8	77
CGI	29.94	15	51	47.69	25	83	67.75	32	112
COU	28.63	17	54	40.44	19	58	60.31	38	121
MKC	27.75	9	58	38.13	26	60	51.19	37	74
SGF	27.50	10	53	40.31	27	70	61.19	28	112
STL	29.00	12	56	37.19	6	60	61.38	38	117
DIK	17.69	5	38	29.13	7	60	40.31	14	83
GFK	18.19	6	37	29.06	5	55	39.44	18	89
MOT	17.19	0	46	26.50	6	53	37.44	11	98
BFF	18.88	0	34	31.50	10	50	45.13	16	71
GRI	20.38	0	43	33.19	23	57	47.88	28	67
OMA	24.94	5	62	39.31	22	64	51.38	38	67
ONL	20.56	0	51	35.25	20	56	47.69	33	61
ABR	17.25	0	40	34.81	11	58	45.06	13	73
FSD	20.31	0	55	34.25	8	61	47.13	15	64
PIR	17.56	0	43	34.13	14	64	46.25	18	70
RAP	16.88	0	36	30.31	16	50	43.19	29	65
GRB	20.00	0	40	40.44	17	70	53.69	6	108
LSE	21.06	0	51	38.94	14	63	52.94	17	82

Table 2-5. South-central Average, Minimum, and Maximum winds, knots

Location	Altitude, MSL								
	6,000 ft.			12,000 ft.			18,000 ft.		
	Avg.	Min.	Max.	Avg.	Min.	Max	Avg.	Min.	Max.
BHM	25.13	7	48	37.63	15	78	54.38	28	88
HSV	27.50	6	47	41.56	18	83	59.19	27	95
MGM	20.69	6	50	31.44	16	62	46.69	24	77
MOB	17.94	0	38	27.38	10	52	43.13	24	80
FSM	25.00	0	52	41.81	18	82	61.13	33	92
LIT	26.75	8	52	41.94	26	68	61.63	36	88
LCH	19.00	0	36	28.06	13	43	44.69	28	68
MSY	17.31	6	33	26.69	9	49	42.44	26	75
SHV	24.94	0	51	38.50	26	60	54.19	29	75
JAN	24.69	8	46	36.75	20	56	51.56	24	78
GAG	25.63	10	42	36.13	20	46	53.19	22	85
OKC	24.25	9	37	36.75	24	57	55.81	27	89
TUL	22.94	0	42	37.88	29	58	58.63	23	98
BNA	30.56	9	49	43.00	16	73	64.00	32	102
MEM	28.19	7	54	42.50	21	69	59.38	34	92
TRI	26.88	0	53	47.75	17	90	63.56	22	112
TYS	28.38	0	48	46.38	15	90	62.00	29	107
ABI	24.81	0	42	34.63	17	53	50.44	25	69
AMA	24.56	6	45	34.19	23	47	50.56	22	78
BRO	19.63	6	29	18.13	0	30	32.38	19	52
CLL	21.25	0	41	31.56	15	48	48.56	32	66
CRP	17.00	0	39	22.19	9	36	40.13	28	61
DAL	25.75	9	47	37.94	28	55	53.88	31	71
DRT	17.31	5	48	29.38	10	48	48.56	26	71
ELP	15.94	0	30	35.38	15	51	51.13	27	71
HOU	20.63	0	40	25.19	12	38	45.44	32	67
INK	19.44	0	39	33.31	16	45	49.56	21	67
LBB	23.06	0	59	32.75	19	45	50.06	28	72
LRD	14.69	6	45	22.50	10	42	40.56	24	65
MRF	N/A[1]	N/A[1]	N/A[1]	31.69	12	52	48.63	14	77
PSX	18.75	0	33	24.06	9	42	42.88	32	62
SAT	17.25	0	48	25.38	0	44	43.88	27	66
SPS	25.63	8	43	36.56	19	64	52.06	28	78
T01	18.00	8	31	23.88	12	35	39.00	27	57
T06	15.94	7	24	21.06	7	35	36.00	25	59
T07	12.56	5	21	18.75	0	36	32.44	19	59
4J3	13.56	5	31	19.88	0	43	30.00	15	56
H51	16.06	0	30	18.06	0	30	32.88	19	45
H52	9.75	0	21	12.63	0	27	26.25	12	44
H61	13.38	5	23	16.94	5	34	21.50	0	39

Note 1: Due to the altitude of the location, the data are not available at 6,000 feet.

Table 2-6. Mountain Average, Minimum, and Maximum winds, knots

Location	Altitude, MSL								
	6,000 ft.			12,000 ft.			18,000 ft.		
	Avg.	Min.	Max.	Avg.	Min.	Max	Avg.	Min.	Max.
PHX	15.06	5	27	31.44	10	46	52.31	32	81
PRC	N/A[1]	N/A[1]	N/A[1]	31.94	5	53	49.75	12	83
TUS	15.50	0	31	32.19	16	53	51.56	25	80
ALS	N/A[1]	N/A[1]	N/A[1]	33.44	19	46	48.50	12	63
DEN	N/A[1]	N/A[1]	N/A[1]	29.25	14	53	46.94	24	65
GJT	N/A[1]	N/A[1]	N/A[1]	28.69	9	43	47.63	23	67
PUB	N/A[1]	N/A[1]	N/A[1]	32.13	14	58	49.56	18	64
BOI	15.06	0	28	23.69	6	51	33.75	5	66
LWS	14.44	0	44	22.25	8	49	35.31	16	69
PIH	13.69	0	24	22.81	0	40	34.88	5	70
BIL	12.50	0	25	22.75	6	56	36.56	14	84
DLN	N/A[1]	N/A[1]	N/A[1]	23.19	13	37	35.50	17	67
GGW	15.25	5	28	24.63	0	50	30.88	0	77
GPI	10.00	0	18	19.38	6	35	33.56	6	57
GTF	10.06	0	29	20.50	6	38	32.69	8	80
MLS	16.44	5	34	25.50	11	53	37.31	14	82
BAM	N/A[1]	N/A[1]	N/A[1]	28.63	10	65	36.13	0	72
ELY	N/A[1]	N/A[1]	N/A[1]	25.38	12	45	34.94	10	59
LAS	17.81	0	40	30.31	7	63	46.75	14	76
RNO	14.56	0	31	31.19	10	61	41.94	16	72
ABQ	N/A[1]	N/A[1]	N/A[1]	34.75	22	50	52.31	34	67
FMN	N/A[1]	N/A[1]	N/A[1]	32.81	22	50	47.19	29	65
ROW	15.81	0	37	34.63	21	52	50.75	28	78
TCC	22.19	0	42	34.00	21	49	52.63	30	81
ZUN	N/A[1]	N/A[1]	N/A[1]	35.25	18	56	52.56	28	71
BCE	N/A[1]	N/A[1]	N/A[1]	29.75	0	53	44.50	0	71
SLC	8.75	0	17	23.69	0	43	32.88	0	66
CZI	N/A[1]	N/A[1]	N/A[1]	26.50	8	44	40.44	19	68
LND	N/A[1]	N/A[1]	N/A[1]	25.81	0	52	37.81	6	64
MBW	N/A[1]	N/A[1]	N/A[1]	34.13	9	56	46.44	10	69
RKS	N/A[1]	N/A[1]	N/A[1]	27.56	9	51	43.19	0	70

Note 1: Due to the altitude of the location, the data are not available at 6,000 feet.

Table 2-7. Pacific Average, Minimum, and Maximum winds, knots

Location	Altitude, MSL								
	6,000 ft.			12,000 ft.			18,000 ft.		
	Avg.	Min.	Max.	Avg.	Min.	Max	Avg.	Min.	Max.
BIH	0.00	0	0	27.19	8	41	39.13	0	76
BLH	18.00	5	28	32.13	13	51	43.94	24	86
FAT	16.81	7	42	27.38	5	48	41.19	13	72

FOT	23.56	5	56	31.56	9	53	42.94	15	72
ONT	18.06	0	34	33.00	0	59	48.31	22	77
RBL	23.19	0	59	31.88	9	56	41.81	15	71
SAC	20.94	0	56	31.38	11	53	40.31	10	74
SAN	18.63	6	30	31.88	11	48	48.00	26	94
SBA	20.50	0	38	35.69	18	62	47.44	23	75
SFO	25.19	8	48	33.56	11	51	42.56	16	69
SIY	20.63	0	45	32.75	9	56	41.94	13	69
WJF	22.06	9	49	33.69	8	59	47.06	22	73
AST	17.44	0	34	29.94	5	52	33.81	0	68
IMB	N/A[1]	N/A[1]	N/A[1]	27.25	8	56	39.00	9	69
LKV	N/A[1]	N/A[1]	N/A[1]	31.19	11	53	40.94	9	78
OTH	15.94	0	45	29.63	8	48	39.19	10	78
PDX	14.94	0	36	29.38	5	53	38.50	0	68
RDM	17.31	0	62	29.75	10	57	42.56	8	77
GEG	12.00	0	23	16.25	0	37	30.13	7	58
SEA	16.81	5	36	23.06	5	48	34.75	13	73
YKM	15.06	0	33	24.81	6	56	39.25	17	79

Note 1: Due to the altitude of the location, the data are not available at 6,000 feet.

3 Summary

The data shows that the average wind speed increases with altitude. For the 6 regions, the average wind speeds are shown in Table 3-1.

Table 3-1. Average wind speed in 6 regions over the continental United States

Region	Altitude, MSL		
	6,000 ft.	12,000 ft.	18,000 ft.
North-east	30.07 knots	48.14 knots	66.94 knots
South-east	18.98 knots	27.83 knots	41.53 knots
North-central	23.26 knots	37.05 knots	51.91 knots
South-central	21.04 knots	31.20 knots	47.56 knots
Mountain	14.48 knots	28.33 knots	42.49 knots
Pacific	17.74 knots	29.68 knots	41.08 knots

The average wind speeds over the continental United States, taking into account the 176 locations, are shown in Table 3-2.

Table 3-2. Average wind speeds over the continental United States

Altitude, MSL		
6,000 ft.	12,000 ft.	18,000 ft.
21.80 knots	33.94 knots	49.04 knots

Light, unpressurized piston aircraft, cruising at altitudes between 0 and 12,000 feet mean sea level

(MSL) will encounter winds speeds averaging 22 to 34 knots. Higher end, pressurized, turbo-prop or jet engine general aviation aircraft cruising at 12,000 to 18,000 feet will encounter winds speed averaging 49 knots and higher.

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14. ABSTRACT
The DAIDALUS Detect and Avoid Algorithm [1] was developed to address the operational needs of Unmanned Aerial Systems (UAS) and meet the Minimum Operational Performance Standards for Detect and Avoid [2]. The DANTi (Detect and Avoid iN the cockpit) concept [3], developed at the National Aeronautics and Space Administration (NASA) Langley Research Center, leverages advancements achieved in surveillance and Detect and Avoid technologies for unmanned aircraft systems as a safety enhancing capability for pilots of manned aircraft.
Pilots operating under Visual Flight Rules and not receiving Air Traffic Control radar services rely on see and avoid to remain well clear of other aircraft and avoid collisions. The DANTi concept has been conceived as a safety enhancement capability to remain well clear and avoid potential collisions. The DANTi concept uses a traffic display to provide situational awareness, conflict detection, alerting, and guidance to remain well clear.

15. SUBJECT TERMS
Conflict Detection and Resolution, Detect and Avoid, Collision, Well Clear, Surveillance, Traffic

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