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Wind Characterization for the Assessment of Collision Risk During Flight Level Changes

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Symbols & Abbreviations

°C	degrees Celsius (temperature)
A	aircraft A
ADS-B	Automatic Dependent Surveillance - Broadcast
Alt	Altitude used in calculations of non-linear wind component
Alt_1	Component of measured wind in the direction of altitude 1
ATC	Air Traffic Control
ATSA	Airborne Traffic Situation Awareness
B	aircraft B
CRM	Collision Risk Model
d_a	Distance to a common point for aircraft A
d_b	Distance to a common point for aircraft B
d_{ITP}	ITP distance
FL	Flight Level
Kft	thousands of feet
kts	knots
ITP	In-Trail Procedure
ITP FL	Initial altitude of the ITP aircraft prior to maneuvering
M	Mach number
mb	millibars (pressure)
N	North latitude (degrees)
NATOTS	North Atlantic Organized Track System
nmi	Nautical Miles
NOAA	National Oceanic and Atmospheric Administration
Reference FL	Altitude of a Reference aircraft used for an ITP maneuver (Ref. FL)

RUC	Rapid Update Cycle
SPR	Safety, Performance and Interoperability Requirements
W	West longitude (degrees)
Wc	Non-linear wind component
σ	Standard Deviation
σ^2	Variance
e	Exponential parameter
x	Rayleigh distribution variable

Abstract

A model of vertical wind gradient is presented based on National Oceanic and Atmospheric Administration (NOAA) wind data. The objective is to have an accurate representation of wind to be used in Collision Risk Models (CRM) of aircraft procedures. Depending on how an aircraft procedure is defined, wind and the different characteristics of the wind will have a more severe or less severe impact on distances between aircraft. For the In-Trail Procedure, the non-linearity of the vertical wind gradient has the greatest impact on longitudinal distance. The analysis in this paper extracts standard deviation, mean, maximum, and linearity characteristics from the NOAA data.

Introduction

The work presented in this paper is the result of the need to consider wind in the collision risk assessment of the In-Trail Procedure (ITP) [1] [2] [3]. The In-Trail Procedure entails the change of flight levels (FL) of an ITP aircraft through the flight level of a Reference aircraft which is not changing altitude. Wind is a significant factor in the change of longitudinal distance during an ITP maneuver. The wind model affects how the wind increases or decreases the longitudinal distance between the aircraft in the Collision Risk Model (CRM). The objective of the analysis presented in this paper is to have an accurate representation of the vertical wind profile and how it affects the ITP; specifically, the non-linear component of the vertical wind profile from one altitude to another.

In-Trail Procedure

The ITP is designed for use in non-radar procedural airspace while aircraft are at cruise altitudes. A complete description of the procedure can be found in the Safety, Performance and Interoperability Requirements (SPR) document for the Airborne Traffic Situation Awareness-ITP (ATSA-ITP) application [4]. The ITP is intended to enable altitude changes that would currently be blocked due to aircraft located at altitude(s) between the current and desired altitudes of a requesting aircraft. This is possible through the use of Automatic Dependent Surveillance – Broadcast (ADS-B), onboard tools, and the new ITP. The following definitions are useful to understand the ITP:

- ITP Aircraft is the aircraft making an ITP request for an altitude change and has the necessary onboard tools, equipment and crew training.

- Reference Aircraft are one or two same direction aircraft at an intermediate altitude, that are transmitting qualified ADS-B data, and that meet the ITP initiation criteria.

- Same Direction occurs when the aircraft tracks or portions of the tracks fall within +/- 45 degrees of each other.

- Same Track is a further restriction of Same Direction that occurs when the protected zones for each track overlap

- Intermediate altitudes include all altitudes between the ITP aircraft’s current altitude and its requested altitude.

- ITP initiation criteria include the following relative ground speed conditions: if the ITP distance to a Reference aircraft is equal to, or more than, 15 nautical miles (nmi), then the groundspeed difference between the two aircraft must be less than or equal to 20 knots (kts); or, if the ITP distance to a Reference aircraft is equal to, or more than, 20 nmi, then the groundspeed difference between the two aircraft must be less than or equal to 30 kts.

- ITP distance is defined as the distance between a Reference aircraft and the ITP aircraft; it is calculated as the difference in distance to a common point along each aircraft's track. There is no requirement that the common point be co-located with any form of navigational waypoint. This is shown graphically in Figure 1.

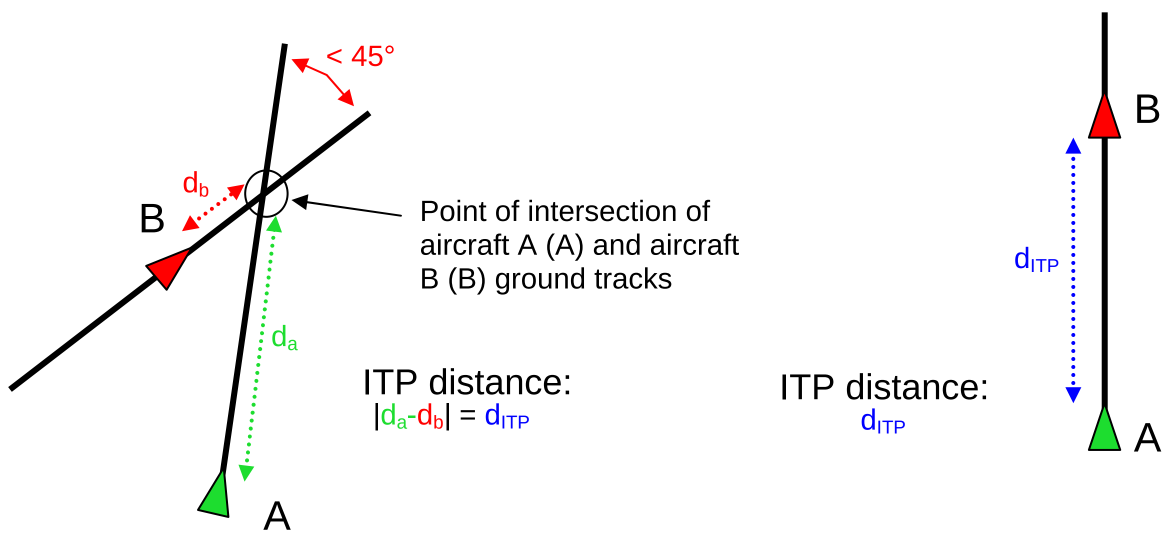

Figure 1. Calculation of ITP distance

The ITP aircraft, using on-board tools, makes use of ADS-B reports from nearby aircraft and determines which of the aircraft have qualified ADS-B data and meet the ITP criteria. The ADS-B reports must meet specific limits for the accuracy and integrity of the data in order to be used for the ITP. In order for the flight crew to request an ITP climb or descent, both the ITP aircraft and any Reference aircraft must be same direction, and the initiation criteria must be met between the ITP aircraft and any Reference aircraft. An air traffic controller must review the request using all available information to ensure separation will exist with all aircraft not involved in the ITP, as well as to ensure that the ITP requirements are met. In order for a controller to approve an ITP, the following conditions must exist:

- the ITP aircraft can not be a Reference aircraft for another ITP clearance;

- the ITP aircraft and each Reference aircraft must be classified as Same Track;

- Reference aircraft can not be in the process of maneuvering or be expected to maneuver; and

- The difference of the ITP and Reference aircraft Mach numbers (M) must be within M0.04 of each other if one aircraft is closing on another.

Upon receiving an ITP clearance from Air Traffic Control (ATC), a flight crew must confirm that the initiation criteria are still met with each Reference aircraft identified in the clearance prior to accepting the clearance and initiating the altitude change. Once the altitude change is completed, the ITP aircraft must report level at the cleared altitude.

The ITP can be applied equally during climb or descent maneuvers. Provided that all of the ITP criteria are met, any of the following aircraft configurations can be used:

1. ITP aircraft following one or two Reference aircraft

2. ITP aircraft leading one or two Reference aircraft

3. ITP aircraft leading one Reference aircraft and following one Reference aircraft

For configurations 1 and 2, if two Reference aircraft are being used, then the aircraft must be located on separate intermediate altitudes. For configuration 3, the two Reference aircraft can be located on the same or separate intermediate altitudes.

Wind Model

The wind model used in this paper considers the case where the winds increase and then decrease from the maneuvering aircraft (ITP aircraft) to the Reference aircraft flight levels. This is shown in Figure 2 where the length of the arrows represents the magnitude of the wind in the direction of flight (headwind/tailwind). Because of the limits imposed by the initiation criteria (groundspeed closure, ITP distance) of the In-Trail Procedure, this wind model provides the largest contribution to the reduction in ITP distance from wind. Four wind models were considered during the collision risk analysis [1]. The other wind models included a continuously increasing wind from the ITP to the Reference aircraft flight levels; a continuously decreasing wind from the ITP to the Reference aircraft flight level; and a constant wind between flight levels.

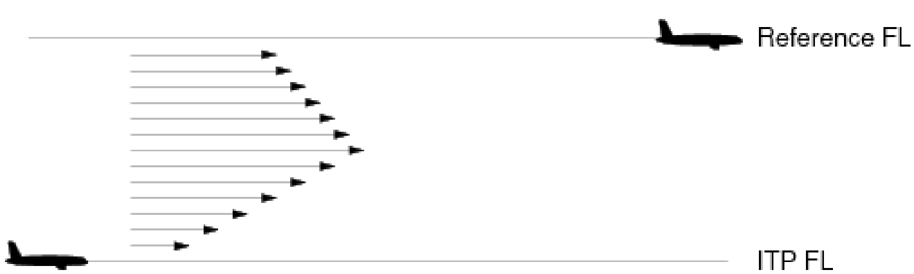

Figure 2. Increasing and decreasing vertical wind profile

This wind model can be analyzed by decomposing the vertical wind profile into two components: one with a linear component that is increasing, decreasing or constant with altitude and one with an increasing and decreasing profile starting and ending with zero magnitude. This decomposition is shown in Figure 3.

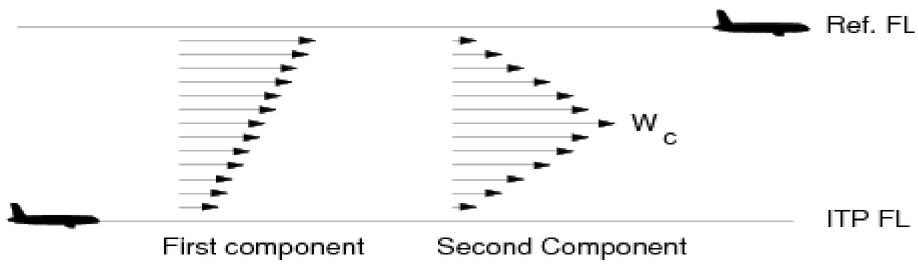

Figure 3. Decomposition of increasing and decreasing vertical wind profile

Note that the first component and second component of Figure 3, when added together, will produce exactly the wind gradient shown in Figure 2. It is shown in reference [1] that the contribution to the reduction of distance by a linear vertical wind profile, as shown by the first component of Figure 3, is bounded by the ITP initiation criteria. However, the second component is not bounded by the initiation criteria and could be arbitrarily large and produce large reductions in aircraft longitudinal distance. The second component of wind is defined by the value Wc which is the wind magnitude at the half way point vertically between the aircraft. A single local maximum was selected due to the fact that it would be unlikely to observe multiple local maxima within the altitude range of 4,000 feet used for the ITP. An example of this can be seen in Figure 7, where there is a local maximum around 26,000 feet and another at around 40,000 feet.

In reference [1], the value Wc was represented by a random variable, and preliminary probability density functions were assigned to the Wc random variable to calculate collision risk. A value of 16.03 kts was used for this preliminary assignment. In this paper, the probability density function of the Wc random variable is derived from National Oceanic and Atmospheric administration (NOAA) wind data. Details of the data used are described in the Wind Data Base section of the paper.

Method to Estimate the Probability Density Function of the Non-linear Wind Component (Wc)

Of greatest interest in this analysis was the non-linear component of the vertical wind profile as represented by the random variable Wc and the probability density function of this variable. Wind nonlinearity is neither measured nor found in wind data reports. Therefore, the non-linear component of the wind must be extracted from existing data and a method to extract this parameter developed. The method used to estimate this parameter represented by the variable Wc was as follows:

- Three wind measurements are obtained at three different altitudes (Alt1, Alt2, Alt3 as shown in Figure 4) with the highest (Alt3) and lowest altitude (Alt1) more than 3000 feet but less than 4000 feet apart.

- The two highest altitude measurements (Alt2 and Alt3 as shown in figure 5) are projected onto the lowest altitude measurement (Alt1) in order to determine the component of each that is in the direction of the lowest altitude measurement.

- A linear interpolation is made between the highest and lowest altitudes.

- The difference between the linear interpolation and the intermediate measurement is obtained.

This is the non-linear component (Wc). (See Example in Figure 6)

Note: The intermediate measurement is not exactly at the middle point between the lowest and highest altitudes. For example, in the data set of Figure 4, the middle point would be 34968 feet. This results in a small error in the calculation of Wc for a given data sample. However, it is expected that on average this error is negligibly small.

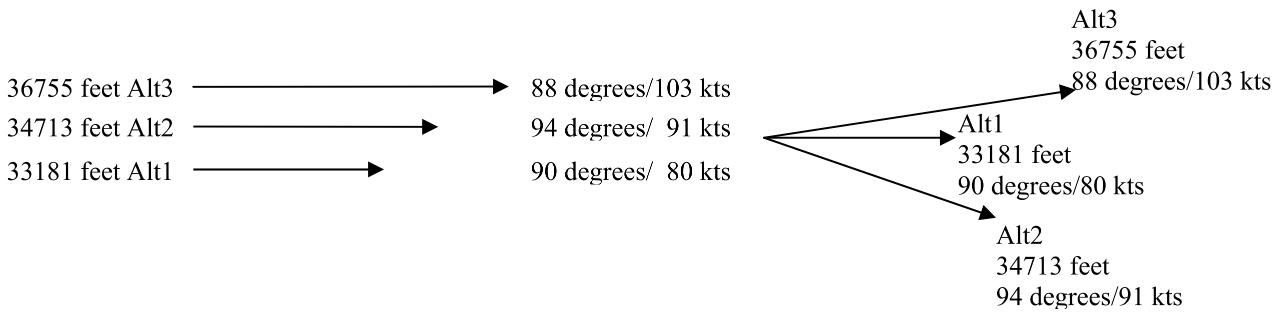

Figure 4. Example wind profile direction and speed at three altitudes; profile and plan view

Figure 5. Projected components of wind at Alt2 and Alt3 in the direction of Alt1; Plan view

The components of Alt 2 and Alt 3 in the direction of Alt 1 (90 degrees) are calculated:

$Alt_1 2 = 91 \cos(90-94) = 90.7783$ kts
$Alt_1 3 = 103 \cos(90-88) = 102.9373$ kts

The linear interpolation of the wind profile is calculated between Alt 1 (33181 feet) and Alt 3 (36755 feet):

$(102.9373 - 80) / (36755 - 33181) = 0.0064$ kts / feet

The wind magnitude following a linear interpolation at Alt 2 (34713 feet) is:

$(34713-33181)0.0064+80 = 89.8321$ kts

The non-linear component of the vertical wind profile is the difference of the linear interpolation and the measured wind:

$|89.8321-90.7783| = 0.95$ kts

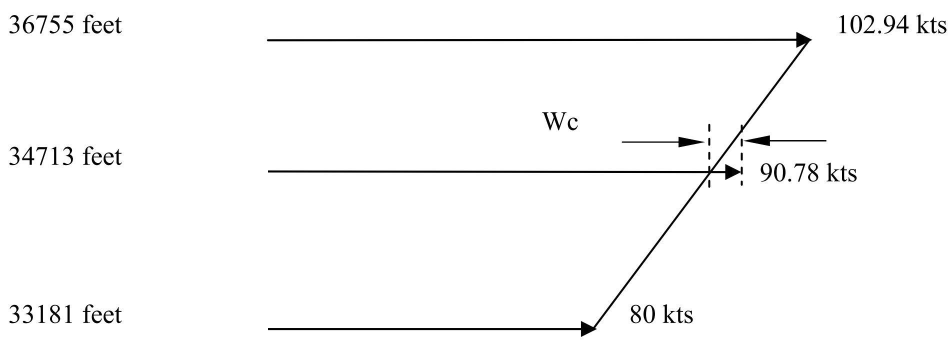

Figure 6. Difference between linear interpolation and measured wind in Alt1 components

This method of estimating the non-linear component was applied to a data base of wind observations spanning several days and different months. The source of the wind data is described in the next section.

Wind Data Base

To estimate the probability density function of Wc, vertical atmospheric profiles were taken from the NOAA Rapid Update Cycle (RUC). An example of the RUC output in graphical form can be seen in Figure 7 [5].

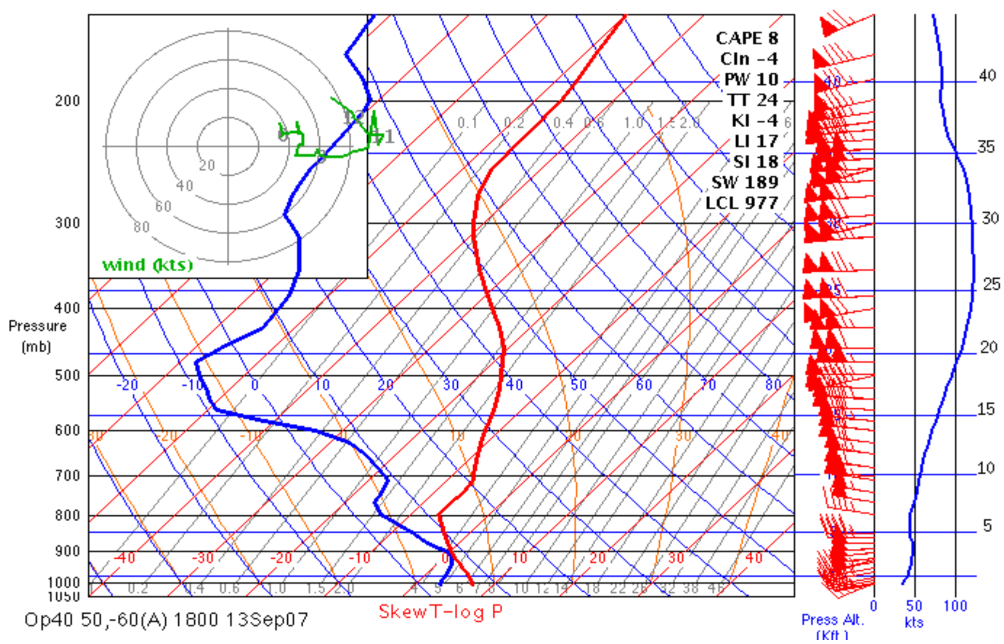

Figure 7. Example of RUC vertical atmospheric profile

The right side of the previous graph (Figure 7) shows the wind magnitude as a function of altitude and the wind direction and magnitude by the wind barbs. These are the data used in the analysis of wind gradient. The vertical axis indicates pressure altitude in 5 thousand feet (Kft) increments. The horizontal axis indicates the wind magnitude in knots. On the wind barbs, the triangles represent increments of 50 kts, the long lines increments of 10 kts, and the short lines increments of 5 kts.

Measurements for winds can also be obtained in tabular form. An example is shown in Table 1. The first column of the table is the pressure altitude in feet. The second column is the pressure in millibars (mb). The third and forth columns are temperature in degrees Celsius (°C). The fifth and sixth columns are true wind direction and wind magnitude. For this study, only the first, fifth and sixth columns were used.

Table 1. Example of RUC soundings in table format

Pressure altitude	Pressure	Temperature	Dewpoint	True Wind direction	Wind speed
(feet)	(mb)	(°C)	(°C)	(degrees)	(kts)
18658	491	-23.5	-27	310°	21
20184	460	-26.4	-31.2	307°	26
23159	405	-33.6	-40.5	299°	31
23451	400	-34.3	-41.3	297°	31
26401	351	-41.7	-49	292°	34
28091	325	-45.3	-55.4	295°	35
29055	311	-46.7	-61	298°	38
29833	300	-47.7	-68	288°	41
29902	299	-47.8	-68.6	301°	41
30581	290	-48.4	-70.8	303°	44
31240	281	-49	-71.2	304°	48
32142	270	-49.6	-71.6	305°	51
32969	259	-50	-72	305°	54
33757	250	-50.3	-72.4	290°	55
33766	250	-50.3	-72.4	305°	55
34400	243	-50.2	-72.4	306°	54
35013	236	-50	-72.5	306°	54
35614	229	-49.9	-72.5	306°	53
36247	223	-49.8	-72.7	307°	51
36923	216	-49.8	-73	308°	48
37589	209	-49.9	-73.5	308°	46
38222	203	-49.9	-74	309°	44
38839	197	-49.8	-74.7	309°	42
39649	190	-49.7	-75.7	309°	40
40879	179	-49.7	-77.6	309°	38

Analysis Results

Two hundred and fifty one RUC vertical wind profiles were obtained from NOAA over the months of May, June, and July 2007. The wind data were mostly at 50 degrees North latitude (50N) and 60 degrees West longitude (60W). These coordinates are approximately at the beginning of the eastbound North Atlantic Organized Track System (NATOTS). It might be of value to expand the data set used in this analysis to include seasonal and geographic variations.

The analysis of the data was limited to pressure altitudes between 20 and 40 thousand feet. It is unlikely that commercial aircraft will cruise at altitudes outside this range. Using the RUC vertical wind profiles, 1773 wind sets were extracted and the method described in the section "Method to Estimate the

Probability Density Function of the Non-linear wind component," was applied to these data. These wind sets required three consecutive altitudes to be able to be used. This allowed for multiple wind sets to be extracted from each RUC profile. Wind average and maximum were also calculated and 3754 individual wind values were used for these calculations.

Wind Nonlinearity

The objective of this analysis was to determine the non-linear characteristic of wind gradient which is the component that has the largest impact on the ITP CRM. The analysis produced the following results:

- Maximum nonlinearity observed (Max Wc): 9 kts
- Average nonlinearity ($\overline{Wc}$): 0.43 kts
- Variance of the distribution (σ^2Wc): 2.39 kts^2
- Standard deviation assuming a Normal distribution (σWc): 1.54 kts

Figure 8 shows a graph of the distribution of Wc.

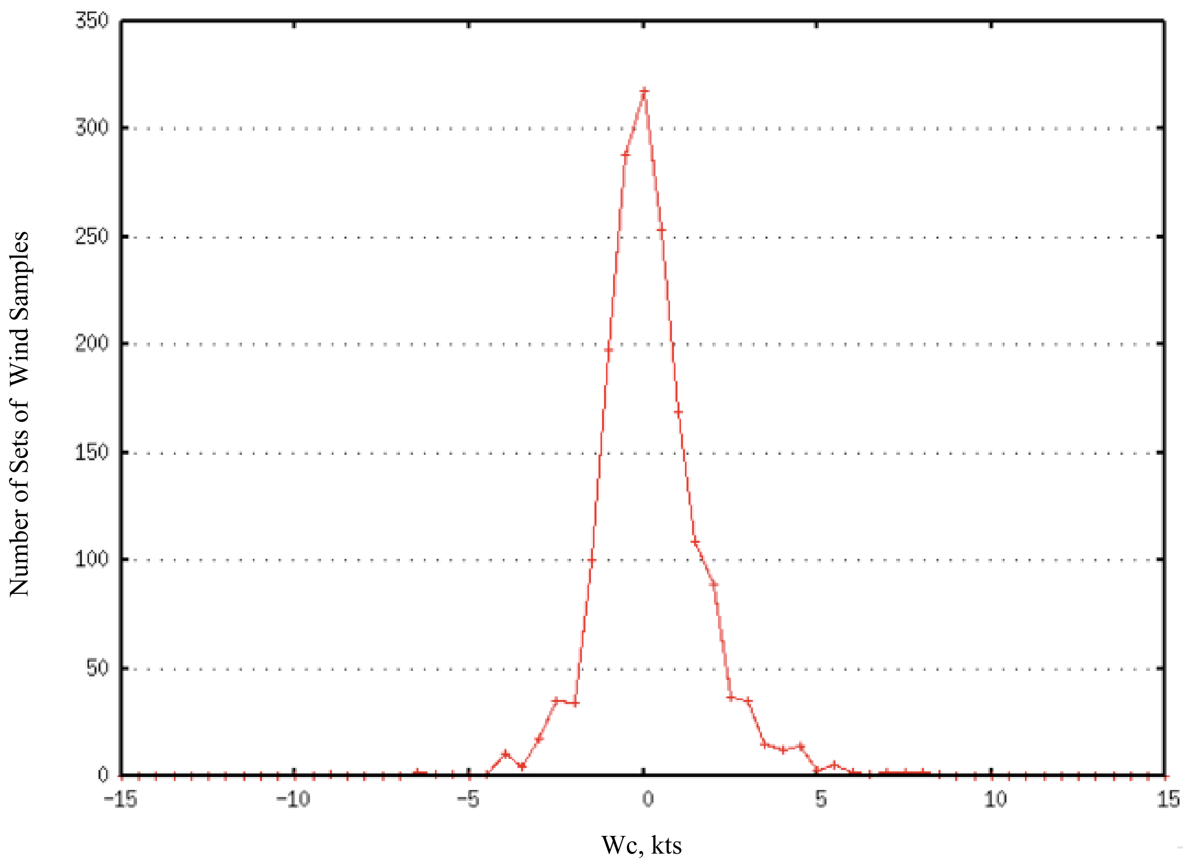

Figure 8. Distribution of Wc for 251 RUC vertical wind profiles obtained from NOAA over the months of May, June, and July 2007

Maximum, Average, and Standard Deviation of Winds from 20 to 40 Thousand Feet

Using the 3754 individual wind values previously described, the maximum, average, and variance of the distribution were calculated for the 251 RUC vertical wind profiles. The distribution approximates a Rayleigh distribution. A Rayleigh distribution has a probability density function of the form:

$$x < 0 \qquad 0$$

$$x \geq 0 \qquad f(x \mid \sigma) = \frac{x e^{\left(\frac{-x^2}{2\sigma^2}\right)}}{\sigma^2}$$

The following results were obtained:

- Maximum wind: 144 kts (at 33461 feet pressure altitude)
- Average wind speed: 47.21 kts
- Variance of the distribution: 864.95 kts^2

Figure 9 shows the graph of the distribution for wind magnitude.

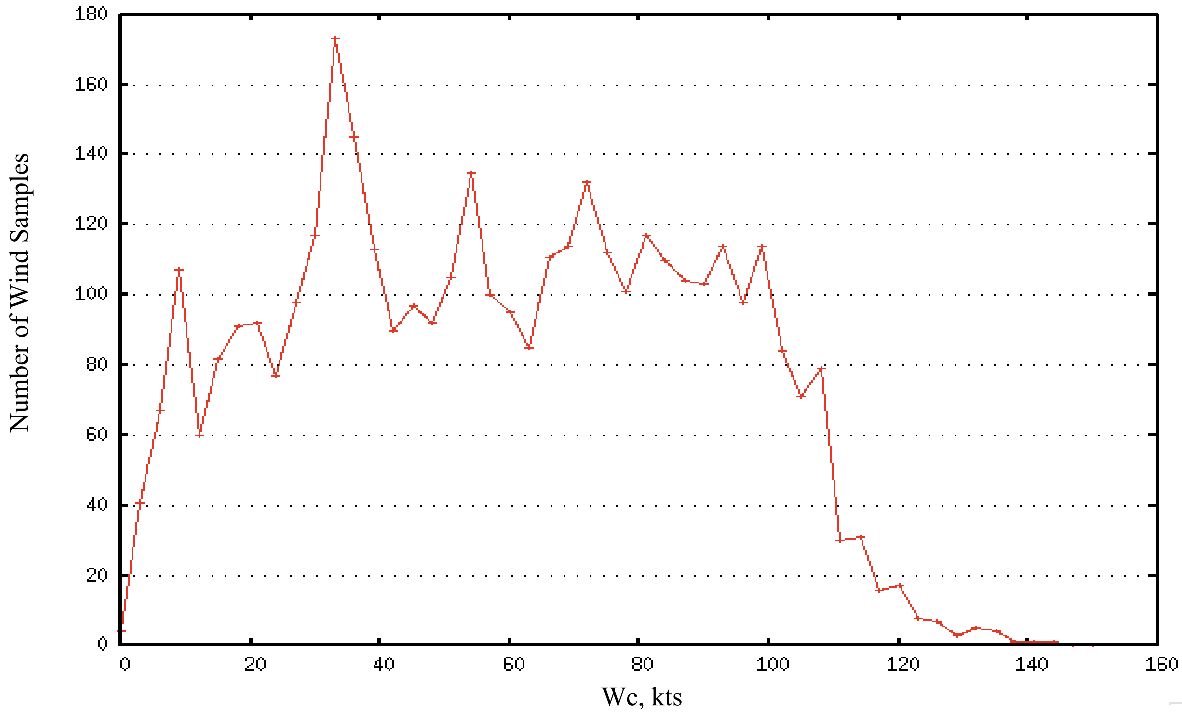

Figure 9. Distribution of wind magnitude over May, June, and July 2007 at (50N, 60W) between 20,000 and 40,000 feet pressure altitude

Summary and Conclusion

This analysis was prompted by the need to characterize the contribution of wind to the reduction in ITP distance when an aircraft is changing flight levels using the ITP. The non-linear aspect of the wind is the most critical factor for the In-Trail Procedure collision risk because it is not bounded by the procedure initiation criteria. The contributions of wind at the ITP flight level and when the ITP and Reference aircraft are co-altitude are bounded by the ground speed and Mach initiation criteria, respectively.

This wind analysis could be expanded to include additional seasonal and geographic variations. Based on this analysis using wind data for May through July 2007, it was found that the standard deviation of the non-linear wind component, Wc, was much smaller than originally assumed. The original standard deviation used in [1] for the non-linear wind component was 16.03 kts. Based on the analysis presented in this paper, the standard deviation for wind nonlinearity will be revised to 1.54 kts.

References

[1] Carreño, Victor: ITP Oceanic Safety Assessment, ICAO Eleventh Meeting of the Working Group of the Whole, Separation and Airspace Safety Panel, Montreal, Canada, May 2007.

[2] Requirements Focus Group: Operational Safety Assessment, In-Trail Procedure In Non-Radar Oceanic Airspace, RTCA/Eurocae, September 2007.

[3] Requirement Focus Group: Application Description, Assessment, In-Trail Procedure In Non-Radar Oceanic Airspace, RTCA/Eurocae, May 2007.

[4] EUROCAE ED-159: Safety, Performance and Interoperability Requirements Document for ATSA-ITP Application, May 2008

[5] Generate soundings from RUC Analyses and Forecasts http://rucsoundings.noaa.gov/

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14. ABSTRACT

A model of vertical wind gradient is presented based on National Oceanic and Atmospheric Administration (NOAA) wind data. The objective is to have an accurate representation of wind to be used in Collision Risk Models (CRM) of aircraft procedures. Depending on how an aircraft procedure is defined, wind and the different characteristics of the wind will have a more severe or less severe impact on distances between aircraft. For the In-Trail Procedure, the non-linearity of the vertical wind gradient has the greatest impact on longitudinal distance. The analysis in this paper extracts standard deviation, mean, maximum, and linearity characteristics from the NOAA data.

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