

WIND SHEAR AND TURBULENCE ANALYSIS

Atlas Business Park Development

Simonsway, Wythenshawe, Manchester, UK

Prepared by: B-Fluid Ltd. | Buildings Fluid Dynamics Consultants

For: Ridge and Partners LLP on behalf of Aviva Investors Global Services UK Limited



Document Reference		
Project Name	WIND SHEAR AND TURBULENCE ANALYSIS Atlas Business Park Development Simonsway, Wythenshawe, Manchester, UK	
Project Ref.	W_2209396	
Site location	Simonsway, Wythenshawe, Manchester M22 5PR, United Kingdom	
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Report issued on	June 7, 2023	

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1. EXECUTIVE SUMMARY

B-Fluid Limited has been commissioned by 'Ridge and Partners LLP on behalf of Aviva Investors Global Services UK Limited' to carry out a Wind Shear and Turbulent Assessment for the proposed Atlas Business Park Development at Simonsway, Wythenshawe, Manchester M22 5PR, United Kingdom. The aim of this study is to assess if the wind shear and turbulence caused by the proposed development, which consists of 5 units of different heights (ranging from approx. 12 m to 20 m), in the vicinity of the Manchester airport runways could cause aircraft instability during landing and take off.

In this report, three sets of guidance documents are used:

- The guidance document, Licensing of Aerodomes (CAP 168) by Civil Aviation Authority (CAA), which emphasizes the importance of a comprehensive risk assessment of any building or structure that could potentially cause wind shear problems;
- The National Airports Safeguarding Framework (NASF) guideline, which points out the acceptance criteria;
- The National Aerospace Laboratory of The Netherlands (NLR) report, which implements a stricter rule on the selection of wind shear impact zones.

In accordance with the NASF guideline and the NLR report, a proposed structure can potentially create a wind shear and turbulence impact risk if located within the trigger area of a nearby runway. The above guideline and report also set the extents and boundaries covered by the respective trigger areas.

If a proposed structure is located within the trigger area, then its acceptability is dictated by the "1:35 height rule" as follows:

- If the building is located at a distance from the centreline of a nearby runway which is more than 35 times the proposed structure height, then the building can be considered acceptable.
- If the building is located at a distance from the centreline of a nearby runway which is less than 35 times the proposed structure height, then a in-depth wind shear and turbulence analysis is required through wind tunnel or CFD modelling to assess the building-induced wind shear and turbulence effects against the acceptance criteria detailed in NLR-CR-2006-261 (known as the "7-knot along-wind criterion", "6-knot cross-wind criterion and "4-knot turbulence criterion").

As shown in the report, the wind shear and turbulence impact of the proposed development on the runways is as follows:

- **Impact on Runway 23L/05R:**

The proposed development is not located within the trigger area Runway 23L/05R according to both the NLR report or the NASF guideline (Table 1.1). Hence, no further analysis is required in relation to Runway 23R/05L as the proposed development, in accordance with the above guidelines does not pose a wind shear and turbulence risk for this runway.

- **Impact on Runway 23R/05L:**

The proposed development is not located within the trigger area of Runway 23R/05L according to the NASF guideline, while it is located within the trigger area suggested by the NLR report (Table 1.2). In addition, as discussed in section 2.1 the height of proposed development exceeds the "1:35 rule" for Runway 23R/05L. Hence, the effects of this development are further analyzed in this report through CFD analysis in relation to Runway 23R/05L.

Tables 1.1 and 1.2 summarize if the proposed units are located within any trigger area for each of the runways and specifies the distances of each unit from the runways in relation to the "1:35 rule".

Table 1.1: Trigger Areas and the 1:35 Rule for Runway 23L/05R

Building units	Runway 23L/05R					
	Trigger Area		1:35 Rule			
	NASF	NLR	Unit height	1:35 Distance	Distance to centreline	Is 1:35 rule penetrated?
Unit 1	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 2	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 3	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 4	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 5	Outside	Outside	N.A.	N.A.	N.A.	N.A.

Table 1.2: Trigger Areas and the 1:35 Rule for Runway 23R/05L

Building units	Runway 23R/05L					
	Trigger Area		1:35 Rule			
	NASF	NLR	Unit height	1:35 Distance	Distance to centreline	Is 1:35 rule penetrated?
Unit 1	Outside	Within	19.3 m (11.8 m above runways)	675.5 m	215 m	Yes
Unit 2	Outside	Within	16.8 m (9.3 m above runways)	588 m	191 m	Yes
Unit 3	Outside	Within	16.8 m (9.3 m above runways)	588 m	129 m	Yes
Unit 4	Outside	Within	16.8 m (9.3 m above runways)	588 m	20 m	Yes
Unit 5	Outside	Within	19.8 m (12.3 m above runways)	693 m	80 m	Yes

The analysis, which assesses the wind shear and turbulence impact against the acceptance criteria of NLR-CR 2006-261, demonstrates the following:

- 7 Knot along-wind criterion:
 - For approaching wind speed 5m/s (9.8 Kts), 10m/s (19.4 Kts) and 15 m/s (29.2 Kts), the NLR "7 Knot criterion" is never exceeded.
- 6 Knot across-wind criterion:
 - For approaching wind speed 5m/s (9.8 Kts), 10m/s (19.4 Kts) and 15 m/s (29.2 Kts), the NLR "6 Knot criterion" is never exceeded.
- 4 Knot turbulence criterion:
 - For approaching wind speed 5m/s (9.8 Kts), 10m/s (19.4 Kts) and 15 m/s (29.2 Kts), the NLR "4 Knot criterion" is never exceeded.

2. PROJECT DESCRIPTION

2.1 INTRODUCTION

B-Fluid Limited has been commissioned by 'Ridge and Partners LLP on behalf of Aviva Investors Global Services UK Limited' to carry out a Wind Shear and Turbulent Assessment for the proposed Atlas Business Park Development at Simonsway, Wythenshawe, Manchester M22 5PR, United Kingdom. The aim of this study is to assess if the proposed development, which consists of 5 units of different heights (ranging from approx. 12 m to 20 m), located in the vicinity of the Manchester airport could pose a risk for wind shear and turbulence on the nearby runways (Runway 23R/05L and Runway 23L/05R).

For this assessment, three sets of guidance documents are used:

- The guidance document, Licensing of Aerodomes (CAP 168) by Civil Aviation Authority (CAA), which emphasizes the importance of a comprehensive risk assessment of any building or structure that could potentially cause wind shear problems;
- The National Airports Safeguarding Framework (NASF) guideline, which provides world-class guidance on airport design and is recognized by International Civil Aviation Organization (ICAO) and CAA;
- The National Aerospace Laboratory of The Netherlands (NLR) report, which is a report that provides further explanations on the NASF guideline and is also considered by experts on the subject as world's best practice.

In accordance with NASF Guideline and the NLR report, a proposed structure can potentially create a wind shear and turbulence impact risk if located within the trigger area of a nearby runway.

In NASF guideline, the trigger area is defined as:

- 1200 m or closer perpendicular from the runway centreline (or extended runway centreline);
- 900 m or closer in front of runway threshold (towards the landside of the airport); and
- 500 m or closer from the runway threshold along the runway.

In NLR report, the trigger area is defined as:

- 2000 m or closer perpendicular from the runway centreline (or extended runway centreline);
- 2000 m or closer in front of runway threshold (towards the landside of the airport); and
- 1500 m or closer from the runway threshold along the runway.

Figure 2.1 shows the trigger areas defined in NASF guideline and NLR report.

In accordance with the definitions described above, Figures 2.2 and 2.3 show the location of the development in relation to the trigger areas of Runway 23R/05L and Runway 23L/05R defined by NASF guideline and the NLR report. More details on the trigger areas can be found in Section 4.2.

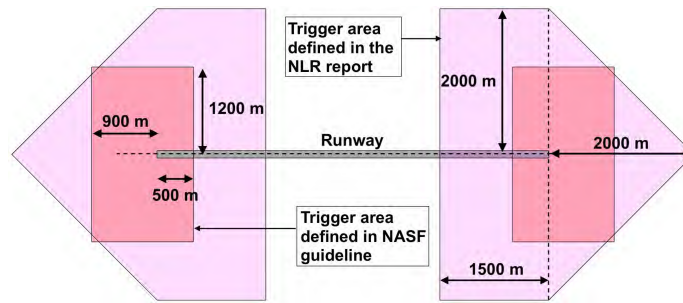


Figure 2.1: Trigger Areas Defined in NASF Guideline and NLR Report

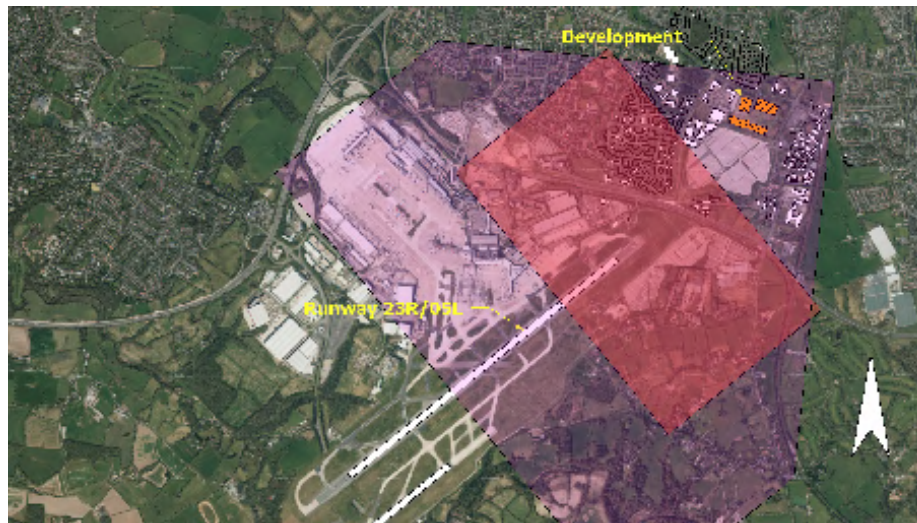


Figure 2.2: NASF Trigger Area (Colored in Red) and NLR Trigger Area (Colored in Violet) of Runway 23R/05L



Figure 2.3: NASF Trigger Area (Colored in Red) and NLR Trigger Area (Colored in Violet) of Runway 23L/05R

According to Figures 2.2 and 2.3, the development is located:

- within the trigger area of Runway 23R/05L according to the NLR report;
- not located within the trigger area of Runway 23L/05R according to both the NASF guideline and the NLR report.

In accordance with the NASF guideline and the NLR report, if a proposed structure is located within the trigger area, then its acceptability is dictated by the 1:35 rule as follows:

- If the building is located at a distance from the centreline of a nearby runway which is more than 35 times the proposed structure height, then the building can be considered acceptable.
- If the building is located at a distance from the centreline of a nearby runway which is less than 35 times the proposed structure height, then a in-depth wind shear and turbulence analysis is required through wind tunnel or CFD modeling to assess the building-induced wind shear and turbulence effects against the NLR-CR-2006-261 acceptance criteria (known as the "7-knot along wind criterion", the "6-knot cross-wind criterion" and the "4-knot turbulence criterion")

Tables 2.1 and 2.2 summarizes if the units are located within any 'trigger area' for both the runways and specifies the distances of each unit from the two runways in relation to the "1:35 rule".

It is noted that the units within the development are on a terrain level that is approximately 7.5 m lower than the level of the runways. However, calculations of the distances based on the "1:35 rule" are conducted using the actual heights of the building units for conservative purposes.

Table 2.1: Trigger Areas and the 1:35 Rule for Runway 23L/05R

Building units	Runway 23L/05R					
	Trigger Area		1:35 Rule			
	NASF	NLR	Unit height	1:35 Distance	Distance to centreline	Is 1:35 rule penetrated?
Unit 1	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 2	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 3	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 4	Outside	Outside	N.A.	N.A.	N.A.	N.A.
Unit 5	Outside	Outside	N.A.	N.A.	N.A.	N.A.

Table 2.2: Trigger Areas and the 1:35 Rule for Runway 23R/05L

Building units	Runway 23R/05L					
	Trigger Area		1:35 Rule			
	NASF	NLR	Unit height	1:35 Distance	Distance to centreline	Is 1:35 rule penetrated?
Unit 1	Outside	Within	19.3 m (11.8 m above runways)	675.5 m	215 m	Yes
Unit 2	Outside	Within	16.8 m (9.3 m above runways)	588 m	191 m	Yes
Unit 3	Outside	Within	16.8 m (9.3 m above runways)	588 m	129 m	Yes
Unit 4	Outside	Within	16.8 m (9.3 m above runways)	588 m	20 m	Yes
Unit 5	Outside	Within	19.8 m (12.3 m above runways)	693 m	80 m	Yes

Therefore, this report includes the analysis of the impact of the proposed units in relation to Runway 23R/05L because they are located within this runway ‘trigger area’ (due to the extents of the trigger area boundaries defined by the NLR report) and their heights exceed the “1:35 rule” for the same runway.

A in-depth analysis was carried out and covered in this report, using a quantitative Computational Fluid Dynamics (CFD) analysis to calculate if the wind shear and turbulence effect caused by the proposed development on Runway 23R/05L is within the acceptance criteria.

Figure 2.4 shows a view of the proposed development (colored in orange) in the existing urban context. Figures 2.5 and 2.6 provide realistic rendering views of the proposed development.

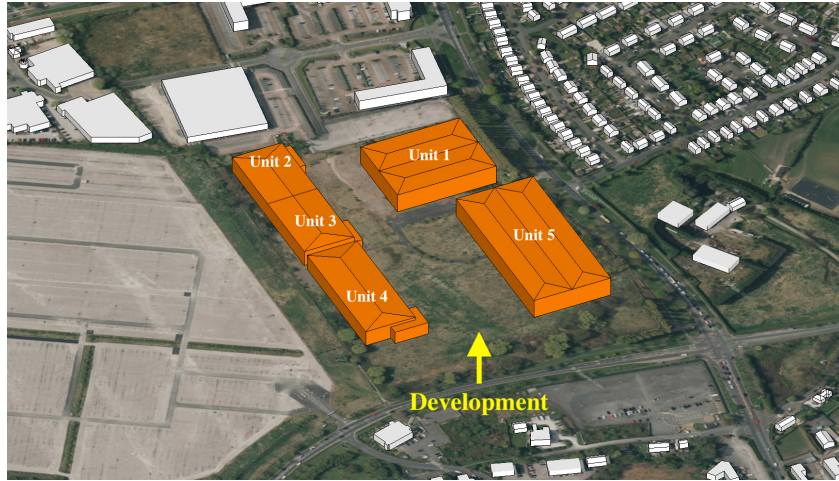


Figure 2.4: Proposed Atlas Business Park Development (colored in orange)



Figure 2.5: Proposed Atlas Business Park Development - Realistic Rendering - Street View



Figure 2.6: Proposed Atlas Business Park Development - Realistic Rendering - Ariel View

This report is completed by Dr. Cristina Paduano, Dr. Arman Safdari and Dr. Yuxiang Zhang.

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Dr. Yuxiang Zhang is a CFD Engineer who specialises in flow-structure interactions and bridge aerodynamics. He holds a PhD in Civil Engineering from University College Dublin, a M.Sc. in Structural Engineering and a B.Eng in Civil Engineering.

2.2 OBJECTIVE OF THE ANALYSIS

The objective of this study is to analyse the wind shear and turbulence conditions after the construction of the proposed Atlas Business Park Development in order to make sure that the development does not increase the risk of building-generated windshear and building-generated turbulence near runways at the Manchester airport.

2.2.1 WINDSHEAR and TURBULENCE IMPACT on AIRCRAFT

Windshear refers to the situation where the wind changes direction or speed suddenly, over a short distance. It can be vertical or horizontal, affecting an aircraft either as it takes off or descends, or its horizontal flight path.

It is well known in aviation that windshear is often experienced near weather front in the form of microburst/downburst, this is often felt as 'turbulence' and often occurring at high altitude (see Figure 2.7).

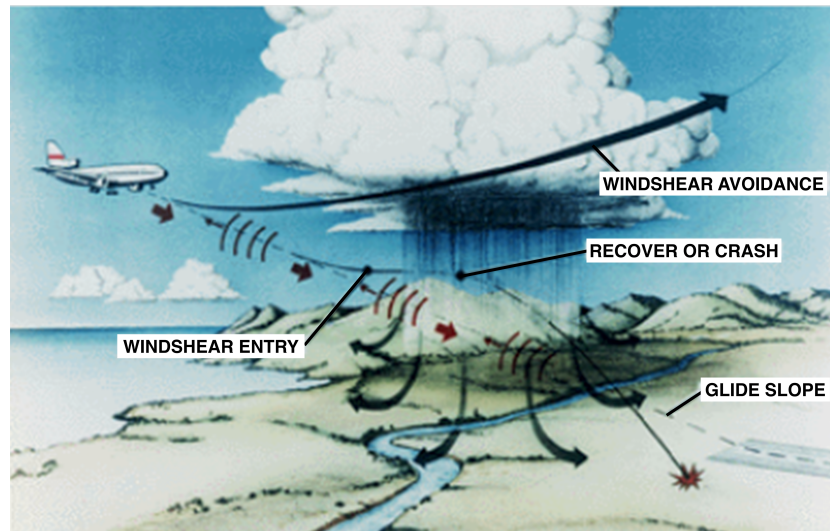


Figure 2.7: Wind Shear and Turbulence due to Weather Conditions

Windshear, however, can be also experienced at low altitude and near the ground. Near airports, where the air flows over obstructions, such as bluffs, hills, trees, or buildings, the normal horizontal wind flow is indeed disturbed and transformed into a complicated pattern of eddies and other irregular air movements (see Figure 2.8).

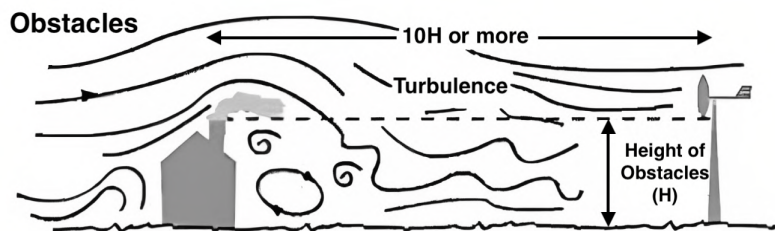


Figure 2.8: Wind Shear and Turbulence Due to Obstacles on the Ground

The risk of wind shear, in both cases above, consists in the sudden change in the wind and its resulting effect on the aircraft's lift. If the wind speeds change, the lift of the airplane changes as well, and the pilots need to re-adjust the aircraft to the desirable lift by increasing/reducing engine power appropriately and in relation to the altitude. While this operation is quite standard at high levels, it can be more difficult close to the ground, during takeoff and landing, as the airplane have little time or room to maneuver. As a consequence, aircraft can be particularly vulnerable to windshear when landing/taking off.

2.3 ACCEPTANCE CRITERIA

As mentioned in the previous section, wind shear and turbulence caused by buildings in the vicinity of airports can cause aircraft instability during landing or take-off.

The instability which building-induced wake effects can cause to an aircraft is significantly reduced once the aircraft has touched down (upon landing) or is at reasonable height (200 ft off the ground prior to landing). After touch-down, the aircraft has increased stability/support from contact with the runway pavement and above 200 feet, both the consequences of a drop in altitude or a change in wind bank are considerably less and the pilot has increased latitude and so time to correct an induced effect on the aircraft prior to touch-down.

In accordance with NASF Guideline and the NLR report, a proposed structure can potentially create a wind shear and turbulence impact risk if located within the trigger area of a nearby runway.

If a proposed structure falls inside the trigger area, then its acceptability is dictated by the "1:35 height rule", which can be explained as follows:

- **Any proposed development located at a distance of at least 35 times its own height from the centreline of a runway will not pose a risk of wind shear and turbulence on the runway.**
- **Whilst, any proposed building which is located at a distance below 35 times its own height, need to be further assessed for potential wind shear and turbulence effects on that runway - i.e. "the building height exceeds the 1:35 rule"**

When the building height exceeds the "1:35 rule", the following acceptance criteria must be applied as stated in the NLR report (NLR-CR-2006-261) to decide if the building in question can be accepted or not:

- *The "7-knot (3.6 m/s) along wind criterion"*: the variation in mean wind speed due to wind disturbing structures must remain below 7 Kts (3.6 m/s) along the aircraft trajectory at heights below 200 ft. The speed deficit change of 7 Kts must take place over a distance of at least 100 m.
- *The "6-knot (3.09 m/s) cross-wind criterion"*: the variation in mean wind speed due to wind disturbing structures must remain below 6 Kts across the aircraft trajectory at heights below 200 ft. The speed deficit change of 6 knots must take place over a distance of at least 100 m.

- The “4-knot (2.06 m/s) turbulence criterion”: the standard deviation of wind speed must remain below 4 Kts at heights below 200 ft.

The wind shear criteria are depicted schematically in Figure 2.9.

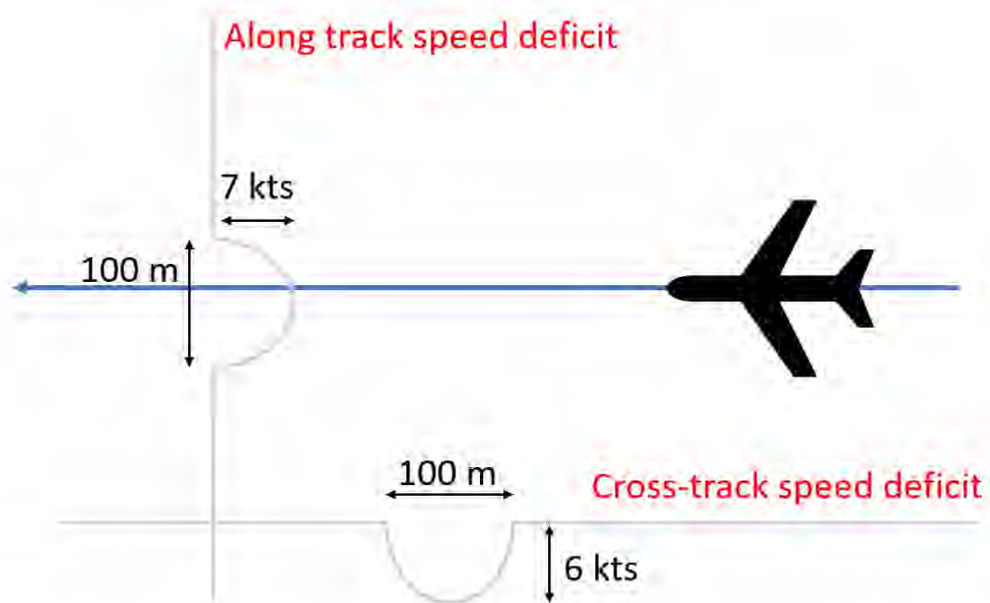


Figure 2.9: Wind Shear and Turbulence Criteria

3. STUDY METHODOLOGY

This chapter reports the summary of the assessment methodology used to carry out the CFD analysis. Results determined using this methodology can be found in Appendix A 'CFD Results'. Verification and validation of the methodology is presented in Appendix B.

3.1 METHODOLOGY of ANALYSIS

The assessment has been carried out through the following steps:

- **"Step 1 - Local Weather Data Analysis"**: A statistical analysis of 30 years of historical weather wind data has been carried out to calculate wind shear and natural turbulence exceedance probabilities data at Manchester Airport.
- **"Step 2 - 3D CFD Model of the Complex Environment"**: A model has been produced for scenarios including the proposed development, topography, nearby existing buildings and relevant features at the areas of interest (see Figure 3.1).



Figure 3.1: 3D Model of the Simulation Scenario

- **"Step 3 - Wind Shear and Turbulence Predictions"**: In this case simulations at different wind speeds and magnitudes have been implemented to assess if the wind shear and turbulence caused by the new development in the vicinity of the 23R/05L and the 23L/05R runways can cause aircraft instability during landing/ take off.

For this step, different wind directions have been analysed, these are the wind directions that are generating a wake from the building which can cause wind shear and turbulence risk.

It must be noted that the wake of a building can cause wind shear and turbulence effects when it interacts with the airflow near a runway. The wake of a building should be located upwind of the runway to cause wind shear and turbulence effects. This is because the airflow will be flowing towards the runway, and the wake of the building will disrupt this flow.

For the critical wind directions, wind speed and turbulence are collected at the aircraft trajectory, considering 3° and 4° landing/takeoff degrees and assuming that the aircraft glides down with constant speed and its track angle is either 3° or 4° . Six possible paths per each landing degrees are considered. Each path starts at 1200m far from touch down zone and continues to ground level. Airflow velocity and turbulence values are collected along each path. In addition, every 100m across each possible aircraft trajectory, data sampling (for wind velocity and turbulence) were performed per each landing path.

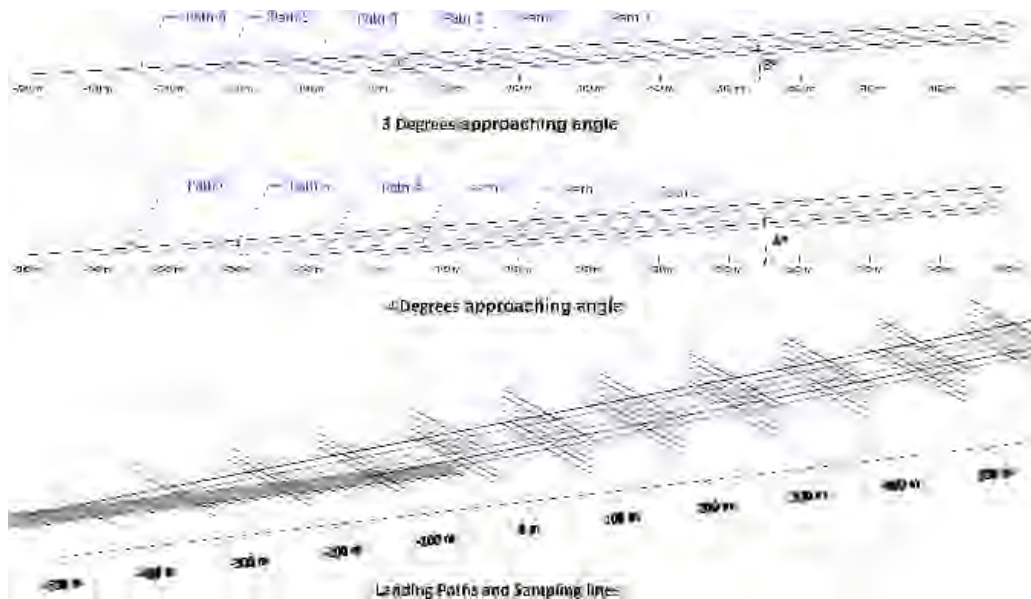


Figure 3.2: Landing Scenarios and Sampling lines at 3° and 4° approaching angle

The velocity and turbulence results are used to obtain the '*Mean Velocity Deficit*' and the '*Turbulence Deviation*' for each of the wind directions and wind speeds, for the assessment of the same against the acceptance criteria.

If any of the acceptance criteria is exceeded, for a particular wind direction and wind speed, then the occurrence of that wind conditions is extracted from the Statistical Weather Data Analysis previously carried out (at Step 1) to predict at which frequency, during a typical year, the wind shear and turbulence level are expected to exceed the critical levels.

4. POTENTIAL IMPACT OF THE PROPOSED DEVELOPMENT

4.1 DEVELOPMENT DESCRIPTION

Application for full planning permission for the severable and phased construction of five units (light industrial (Use Class E(g)(iii), general industrial (Use Class B2) and/or storage or distribution (Use Class B8), together with ancillary offices (Use Class E(g)(i)) providing a total gross external area of 39,536 sqm; and associated service yards, parking, landscaping, amenity space and infrastructure, with vehicular access off Simonsway.

Figures 4.1 and 4.2 show the development units and some existing buildings around the development (the development units are colored in orange).

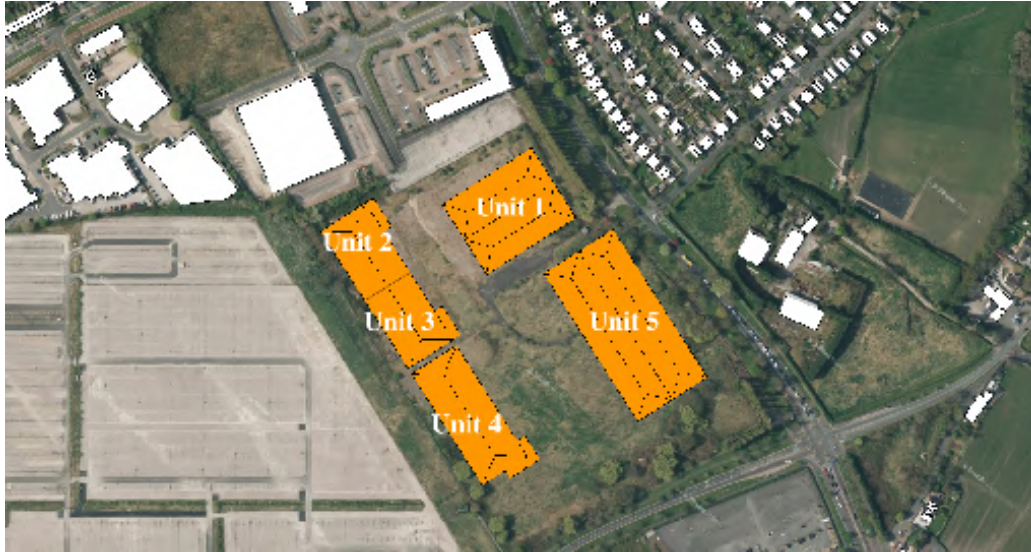


Figure 4.1: Atlas Business Park (colored in orange) - Top View



Figure 4.2: Atlas Business Park (colored in orange) - 3D View

Figure 4.3 shows the location of the site relative to the surrounding build environments.



Figure 4.3: Site Location Relative to the Surrounding Build Environments

Key features of the locality are:

- North: The site is bounded to the north by Simonsway. Further north is a large area of residential houses of 2 to 3 storeys.
- East: East of the site is bordered to an large area of grass land. Further east extends to some commercial and residential buildings of 2 to 3 storeys.
- South: The site is bounded to the south by warehouses. Further south extends to the Manchester Airport.
- West: The site is bounded to the west by Shadowmoss Rd. Further west reaches to residential houses of 2 to 3 storeys.

4.2 IMPACT ON RUNWAYS

The NASF guideline and the NLR report set the size of the zone of potential influence ('trigger area') of a building on a runway based on its distance from the runway centreline as shown in Figure 4.4 below and discussed in section 2.1.

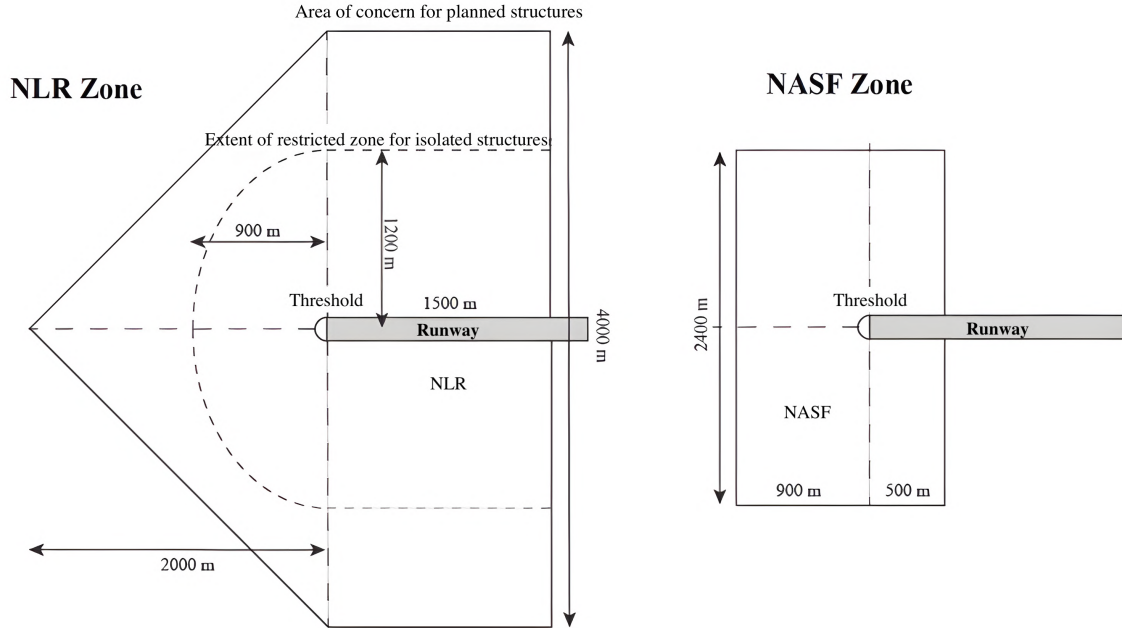


Figure 4.4: Potential Impact Zones Sizes According to the NASF guideline and NLR report

Figures 4.5 to 4.8 show the trigger areas on runway 23R/05L and runway 23L/05R. In these figures, the red zones and purple zones are the trigger area boundaries and extents according to the NASF guideline and the NLR report, respectively.

Findings based on these figures are listed as follow:

- The proposed development is not located within the trigger area of Runway 23R/05L according to the NASF guideline, while it is located within the trigger area suggested by the NLR report. In addition, as discussed in section 2.0.1 the height of proposed development exceeds the "1:35 rule" for Runway 23R/05L. Hence, the effects of this development are further analyzed in this report through CFD analysis in relation to Runway 23R/05L.
- The proposed development is not located within the trigger area Runway 23L/05R according to both the NLR report or the NASF guideline. Hence, no further analysis is required in relation to Runway 23R/05L as the proposed development, in accordance with the above guidelines does not pose a wind shear and turbulence risk for this runway.

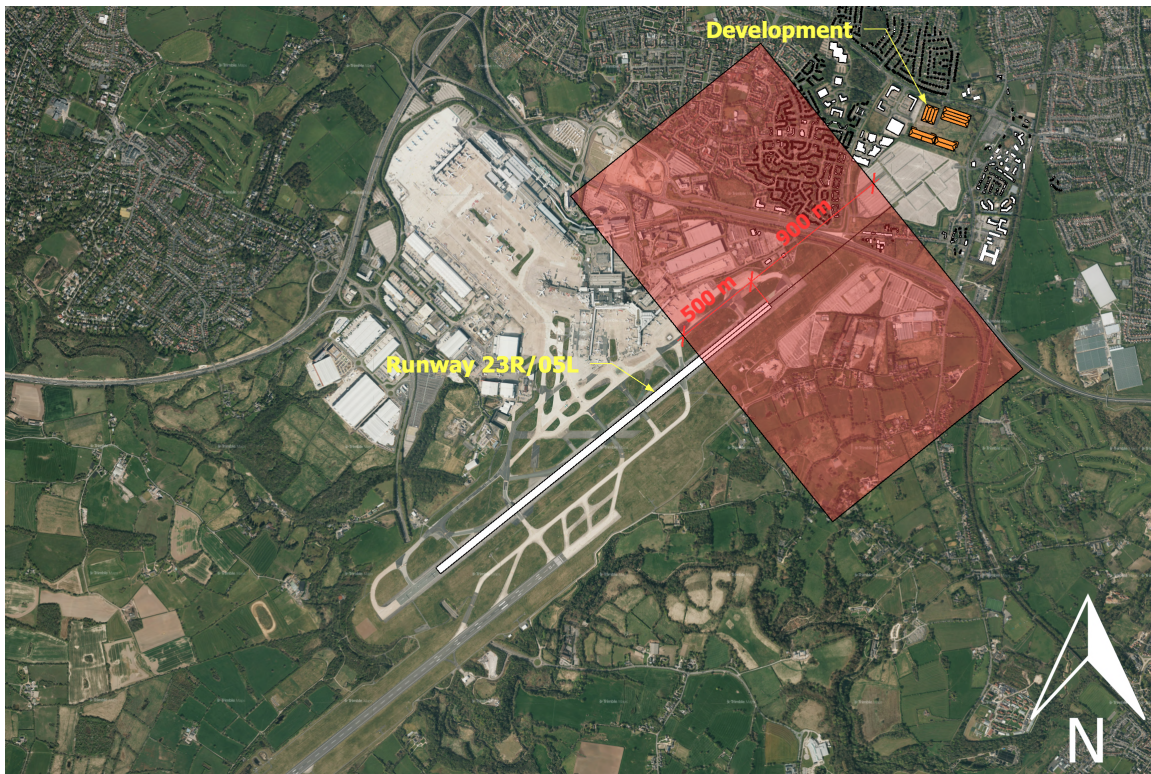


Figure 4.5: Potential Impact Zones on Runway 23R/05L According to the NASF guideline

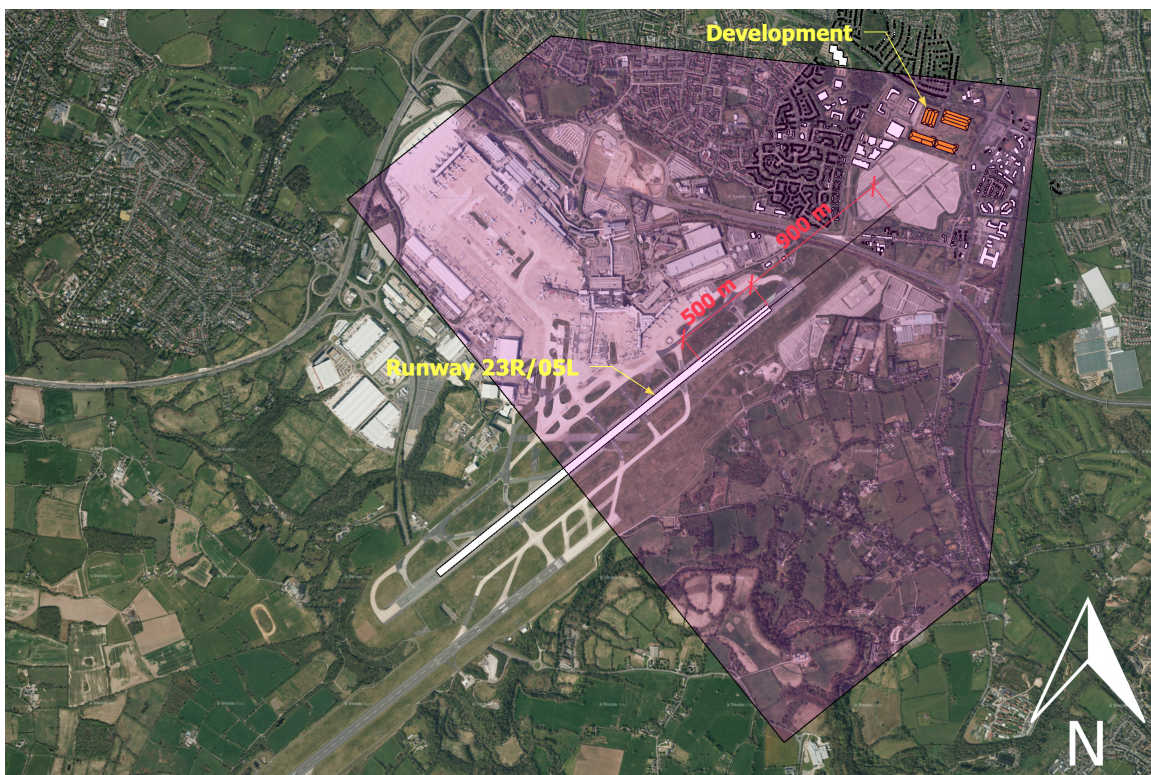


Figure 4.6: Potential Impact Zones on Runway 23R/05L According to the NLR report

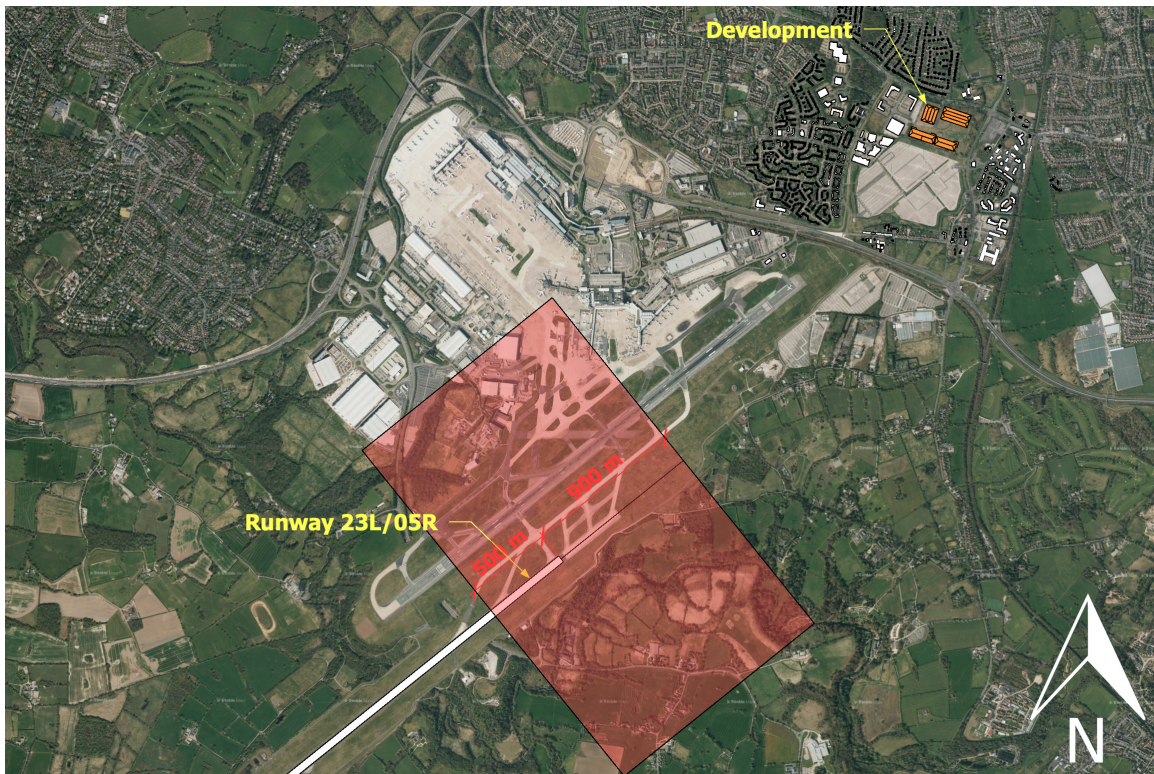


Figure 4.7: Potential Impact Zones on Runway 23L/05R According to the NASF guideline



Figure 4.8: Potential Impact Zones on Runway 23L/05R According to the NLR report

4.3 ASSESSMENT WIND DIRECTIONS

According to the NASF guideline, the modeling for wind shear and turbulent analysis should be conducted along the runway centreline between chainages -900 m to +500 m. In Figure 4.9, the assessment area that covers such range is colored in yellow, and the corresponding wind directions are determined, which are from 20° to 60°. Figure 4.10 shows the three wind directions considered in the wind shear and turbulence analysis, which are 30°, 45° and 60°.



Figure 4.9: The Assessment Area and Corresponding Wind Directions



Figure 4.10: Wind Directions Considered in the Wind Shear and Turbulence Analysis

5. LOCAL WEATHER DATA

5.1 STATISTICAL ANALYSIS OF WIND CONDITIONS

The simulations consider the whole development being exposed to the typical wind condition of the site. The building is oriented as shown in the previous sections. The wind is applied in the CFD model as a velocity boundary condition with a prescribed profile, which specifies the wind magnitude variation with the height and the wind direction.

The wind profile is built using the annual average of meteorology data collected at Manchester Airport Weather Station and provided by Meteoblue.

Figure 5.1 presents the wind gust speeds recorded over a 5-year period between 2018 and 2022. The data is recorded at a weather station at the Manchester airport, which is located 10 m above ground level.

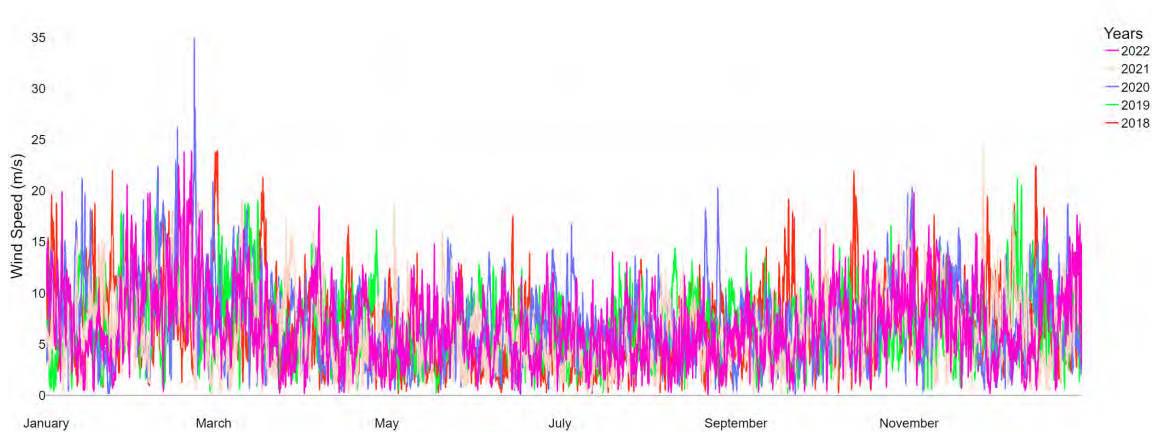


Figure 5.1: Local Wind Conditions - Wind Gust Speed

Figures 5.2 and 5.3 present the wind gust speed diagram for Manchester, which indicates the number of days per month, during which the wind reaches a certain speed.

Figures 5.4 and 5.5 show the frequencies of wind gust speeds at different wind directions based on the weather data collected at the weather station over a period of 10 years between 2008 and 2022.

In Figure 5.6, the wind rose for Manchester airport shows how many hours per year the wind blows from the indicated direction.

Statistical assessment of the weather data is an important part of wind shear and turbulence analysis. Indeed, if any of the acceptance criteria is exceeded, for a particular wind direction and wind speed, then the occurrence of that wind conditions provided by this statistical data enable to predict at which frequency, during a typical year, the wind shear and turbulence level are expected to exceed the critical levels because of the construction of a proposed development.

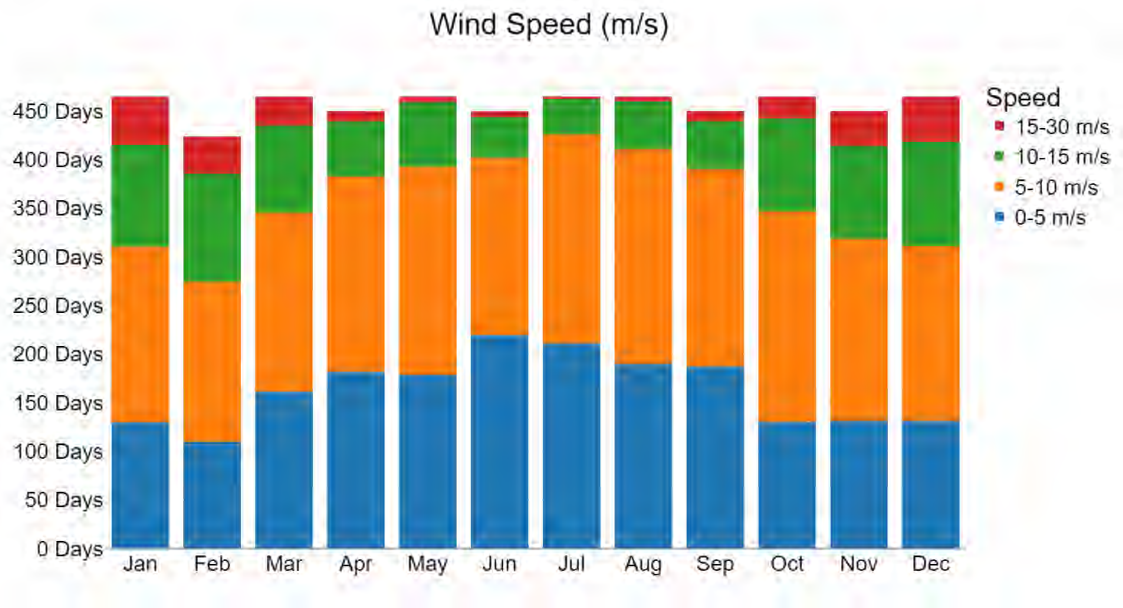


Figure 5.2: Manchester Airport Wind Gust Speed Diagram (from 2008 to 2022) - General View

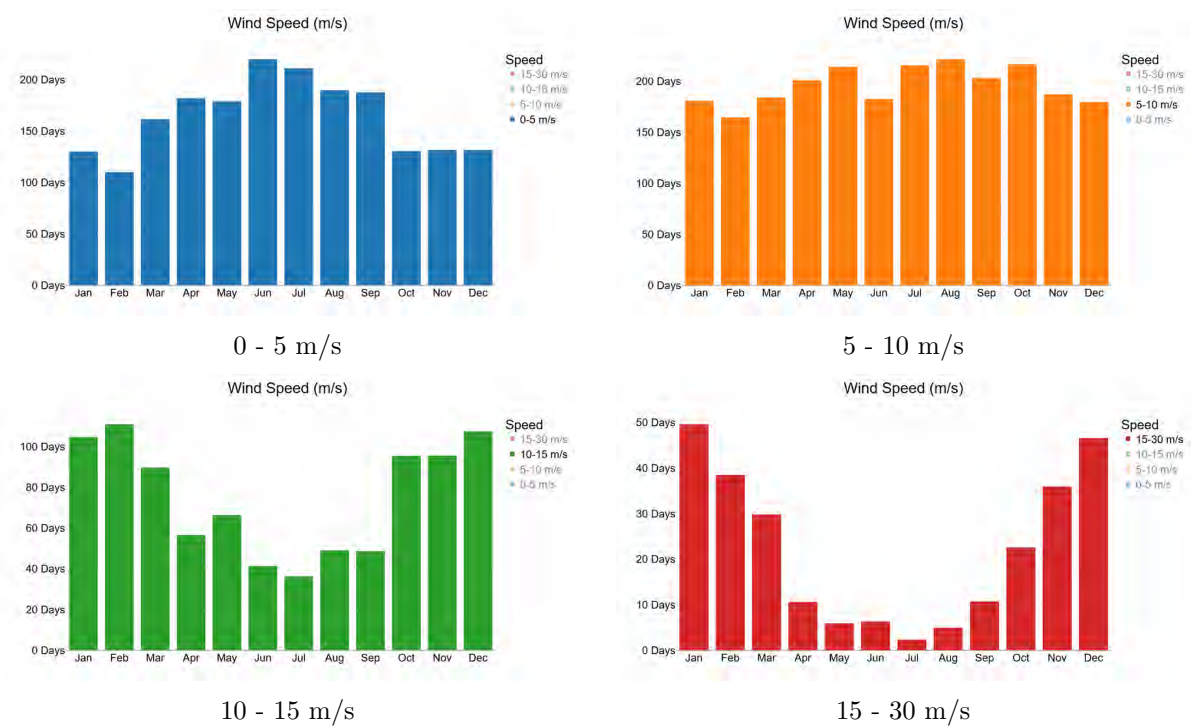


Figure 5.3: Manchester Airport Wind Speed (Gust) Diagram (from 2008 to 2022)

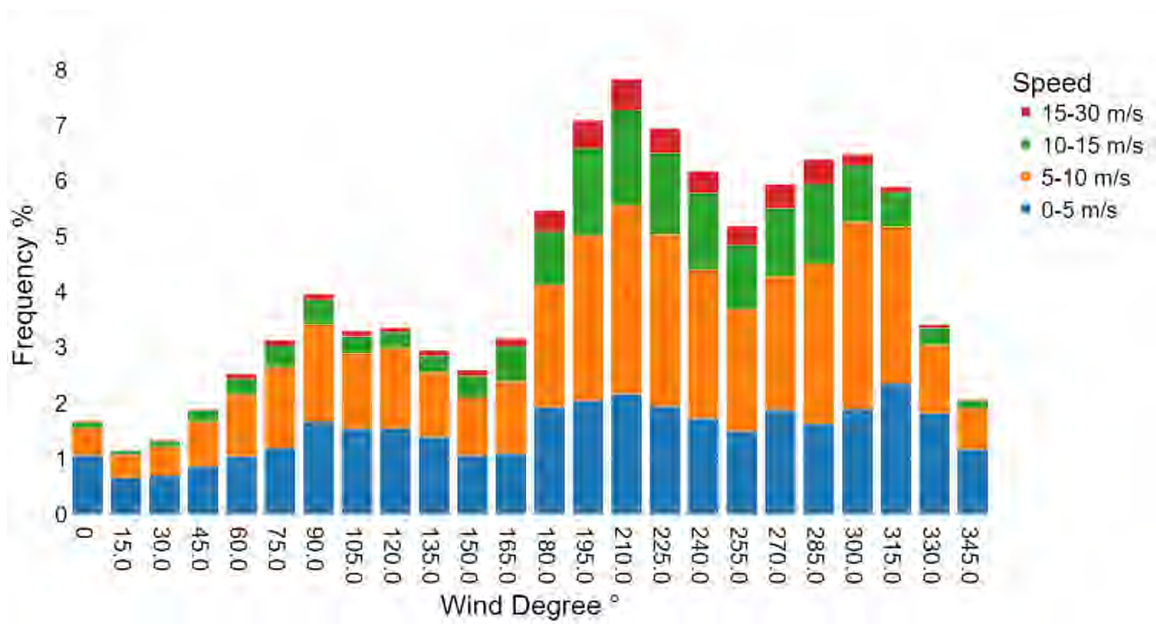


Figure 5.4: Frequency of Wind Gust Speeds at Different Wind Directions (from 2008 to 2022)

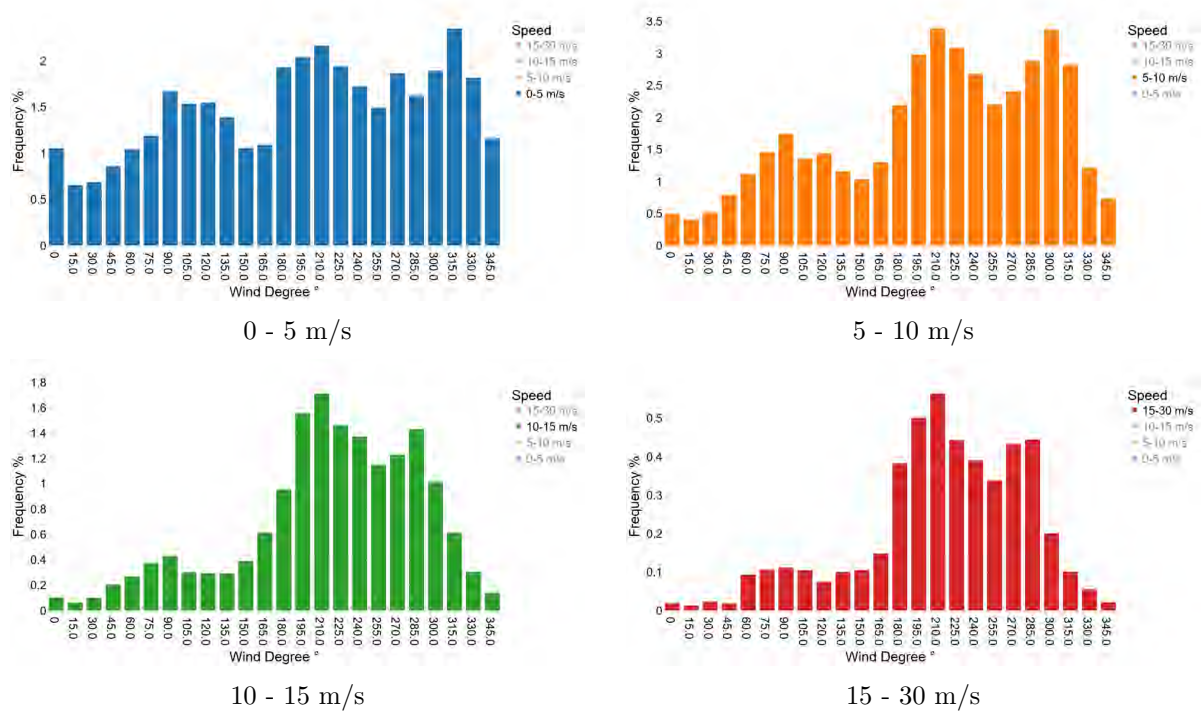


Figure 5.5: Frequency of Wind Gust Speeds at Different Wind Directions (from 2008 to 2022)

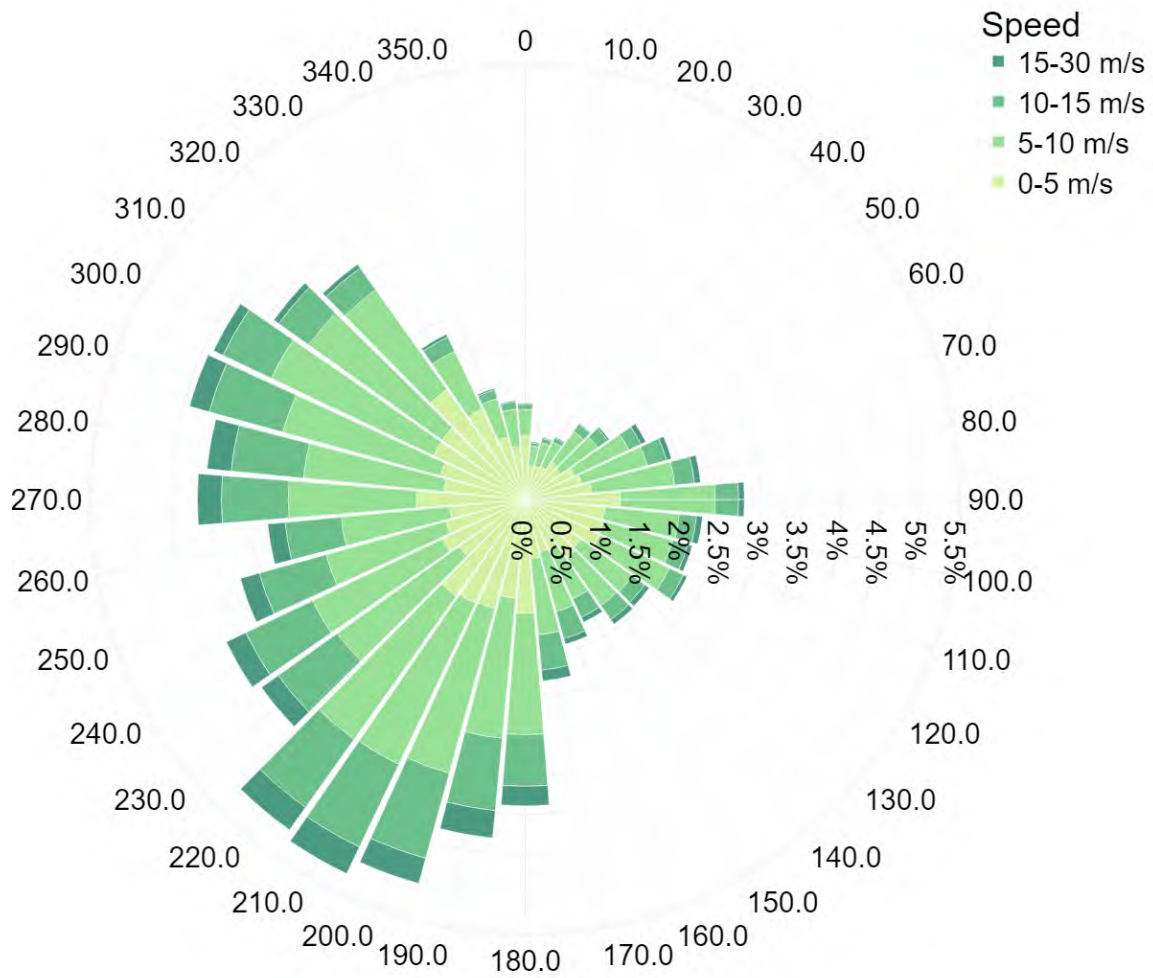


Figure 5.6: Manchester Airport Wind Rose (Gust)

6. CFD MODELLING METHOD

6.1 CFD MODELLING METHOD

In general, wind tunnel testing or Computational Fluid Dynamics (CFD) is required to assess the wind shear and turbulence when a proposed development, which falls inside the NASF or NLR report does not pass the 1:35 rules.

Computational Fluid Dynamics (CFD) is a numerical technique to simulate fluid flow, heat and mass transfer, chemical reaction and combustion, multiphase flow, and other phenomena related to fluid flows. The Navier-Stokes equations, used within CFD analysis, are based entirely on the application of fundamental laws of physics and therefore produce accurate results providing that the scenario modelled is a good representation of reality.

Turbulent (gust) wind flow environment in an urban environment can be modelled with wind tunnel. However, small building features are better modelled in CFD versus wind tunnel testing, where model buildings are typically built to a scale of around 1:400 or similar. This is important when modelling small structures in the vicinity of airports or assessing the benefit of small canopies, porous screens and blades provided to mitigate adverse wind conditions. Moreover, wind tunnel measurements are performed at a few selected points within the tested model while CFD can provide comprehensive output of the entire flow field.

A high number of CFD studies have been published in the International Conferences and Journal of Wind Engineering and Industrial Aerodynamics in the past decades. CFD predictions of wind flow around bluff bodies have been compared and validated against wind tunnel and full scale measurements in the open literature. In general, good correlation is obtained when best practice guidelines are used for the modelling.

6.2 OpenFOAM SOFTWARE DETAILS

This report employs OpenFOAM Code, based on the concept of Reynolds Average Navier Stokes (RANS) and the post-processing visualisation tool Paraview version 5.9. OpenFOAM is a CFD software released and developed primarily by OpenCFD Ltd, since 2004. It has a large user base across most areas of engineering and science, from both commercial and academic organisations. OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to acoustics, solid mechanics and electromagnetics.

In this study unsteady RANS (URANS) simulations with the $k-\omega$ SST turbulence model are used to assess the risks of buildings near the threshold of runways and predict wind shear and turbulence for critical flight paths. The $k-\omega$ SST turbulence model is proposed due to ability to combine the benefits of the standard $k-\epsilon$ model and the $k-\omega$ model while minimising their disadvantages.

In OpenFOAM, the simpleFoam solver is used to perform steady-state RANS simulations. The URANS simulations in this report are performed using the pimpleFoam solver, initialised by the converged results of steady-state simulations.

6.3 MODELLLED GEOMETRIES

The project site is located adjacent to Manchester airport with two parallel operating runways. The airport is an international airport that operates 24 hours a day.

The proposed development is located approx. 1.2km far from the nearest runway at the airport. A 3D view of the proposed development massing model in the domain is presented in Figure 6.1.

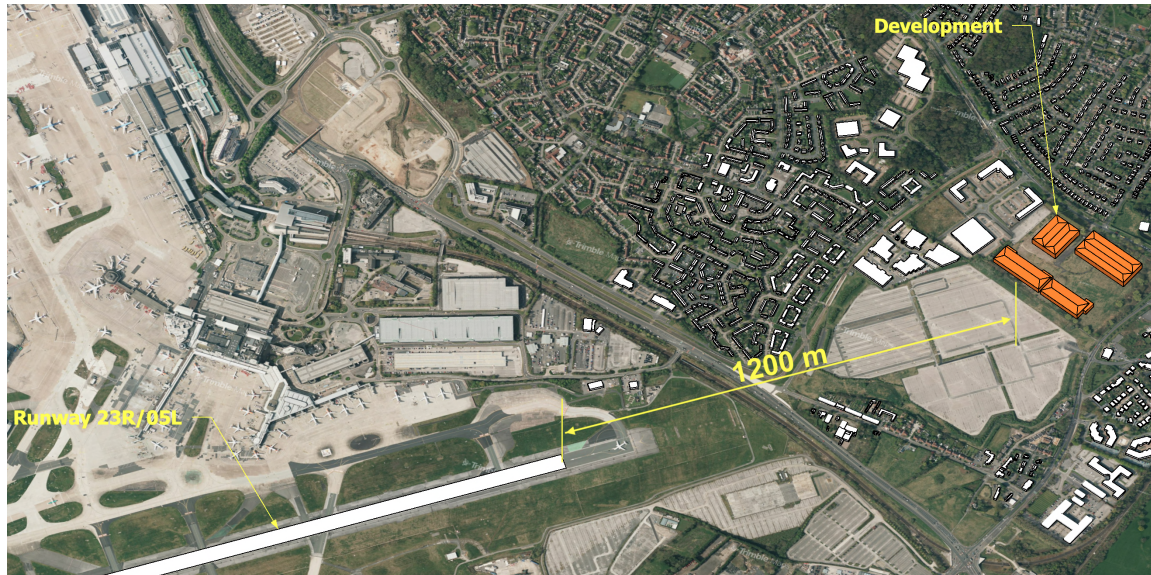


Figure 6.1: Development Site and Geometry for CFD Modelling

The modelled layout and dimensions of the surrounding environment are outlined in the table below (Table 6.1).

The size of the computational domain should be selected according to the best practice guideline. A building with height H may have a minimal influence if its distance from the area of interest is greater than $6-10H$.

In order to represent reality and consider the actual wind impacting on the site, the modelled area for the wind modelling study comprises an area of 600m radius around the development, as shown in Figure 6.2.

	MODELLED CFD ENVIRONMENT DIMENSIONS		
	Width	Length	Height
CFD Mesh Domain	1700m approx	3100m approx	200m approx

Table 6.1: Modelled Environment Dimensions



Figure 6.2: Development Site and Geometry for CFD Modelling

6.4 COMPUTATIONAL MESH

The size of the computational domain should be selected according to the best practice guideline. A building with height H may have a minimal influence if its distance from the region of interest is greater than $6-10H$. All buildings within more than 600m diameter were included in the developed CFD model.

The top of the computational domain should be at least $5H$ away from the tallest building with height H . In order to avoid artificial flow over the building, $10H$ is used in this study where H is the building height.

The level of accuracy of the CFD results are determined by the level of refinement of the computational mesh. Details of parameters used to calculate the computational mesh are presented in Table 6.2. Figures 6.3 and 6.4 show the mesh generated for this project.

The grid follows the principles of the 'Finite Volume Method', which implies that the solution of the model equations is calculated at discrete points (nodes) on a three-dimensional grid, which includes all the flow volume of interest. The mathematical solution for the flow is calculated at the center of each of these cells and then an interpolation function is used by the software to provide the results in the entire domain. Approximately over 40 million cells were used to cover the computational domain per each wind scenarios.

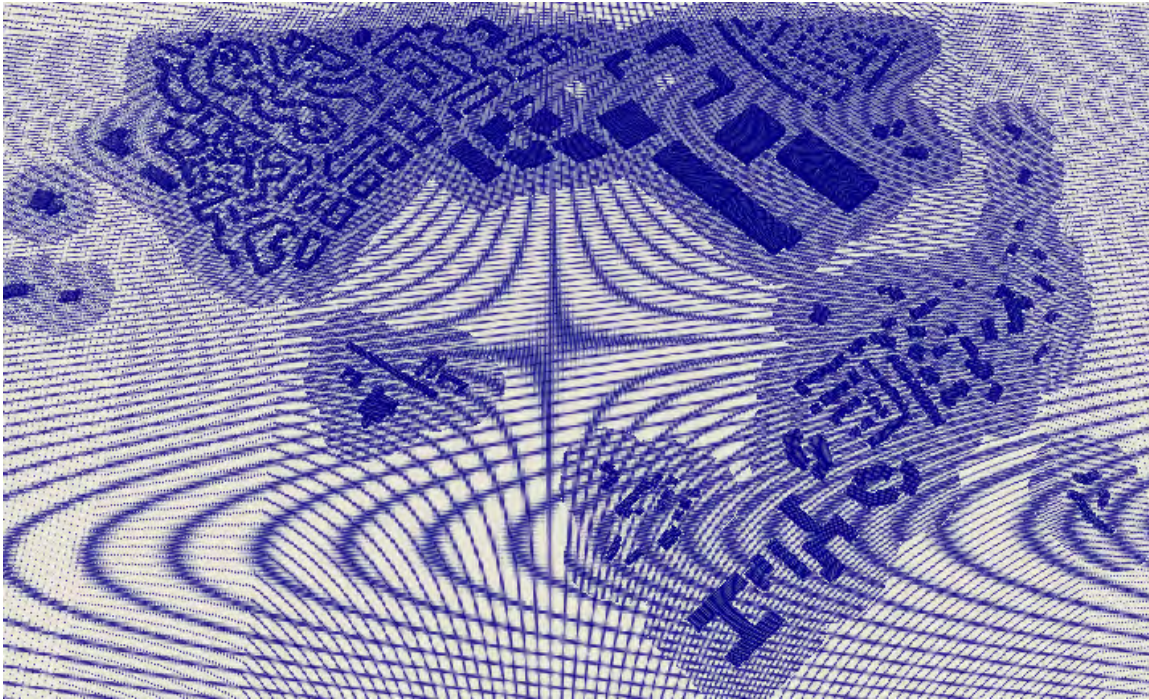


Figure 6.3: Development and Domain Mesh Example

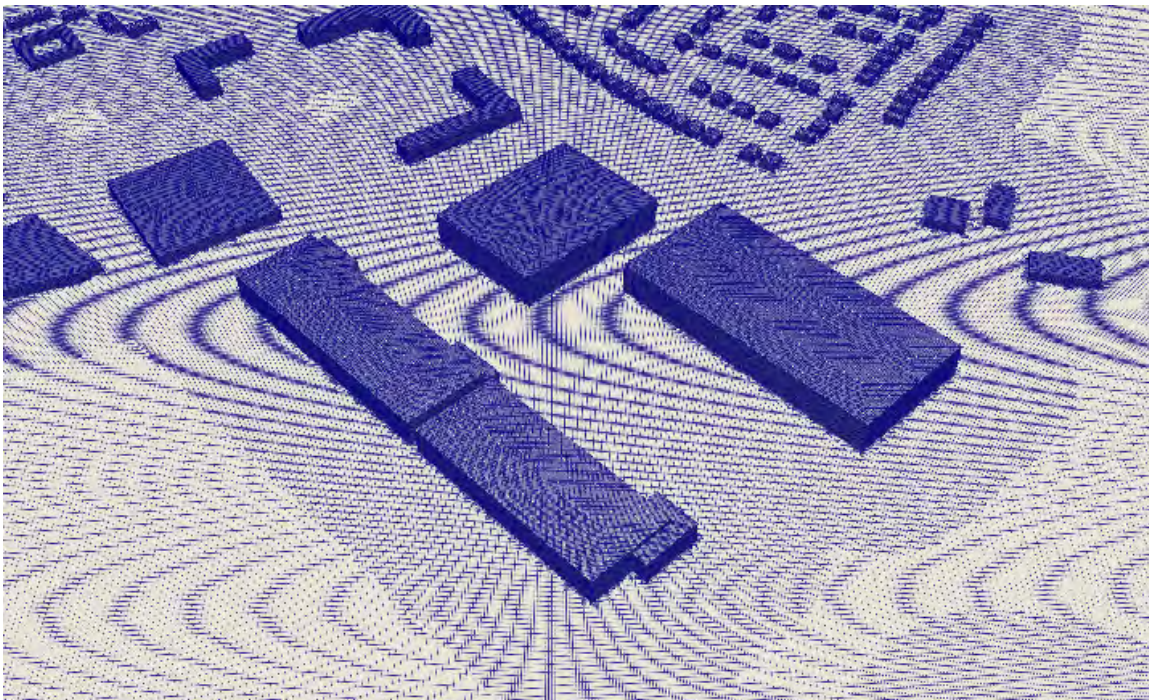


Figure 6.4: Development and Domain Mesh Example - Closer View

6.5 BOUNDARY CONDITIONS

For each wind directions, an initial wind velocity was set based on logarithmic wind profile. Surfaces within the model were specified as having ‘no slip’ condition. This boundary condition ensures that flow moving parallel to a surface is brought to rest at the point where it meets the surface. All the other domain boundaries are set as ”Open Boundaries”.

As unsteady RANS (URANS) simulations require significant computational resources to obtain a valid numerical solution which includes the use of very small time steps (0.01 to 0.02 s) to meet the recommendations in best practice guidelines. The simulations were run in the following way to optimise the computational time:

- Start with a steady-state RANS solution and then switch to URANS model;
- Initially use variable time steps if possible to speed up the simulation;
- Reduce time step as per the best practice guidelines; and then
- Reduce number of iterations per time step if possible.

PARAMETERS TO CALCULATE COMPUTATIONAL MESH	
Air Density ρ	$1.2kg/m^3$
Ambient Temperature (T)	$288K(approx.15^{\circ}C)$
Gravity Acceleration (g)	$9.8m/s^2$
dx	0.175 m at the building 0.7m to 1m in the surroundings 2m to 5m elsewhere
Background Mesh cells ratio	1:1
Total mesh size	Approx. cells number 40 million

Table 6.2: Parameters To Calculate Computational Mesh

6.6 LOGARITHMIC WIND PROFILE

The wind velocity data provided by the historical data collection and by the local data measuring are used in the formula below for the logarithmic wind profile to specify the wind velocity profile (wind velocity at different heights) to be applied within the CFD model:

$$u(z) = \frac{u^*}{K} \cdot \ln\left(\frac{z+z_0}{z_0}\right) \quad (6.1)$$

where:

- $u(z)$ = wind speed measured at the reference height z
- z = height to measure $u(z)$
- z_0 = roughness length (selected according to Eurocode 2005)
- u^* = friction velocity
- K = Karman constant

The wind profile used in the model has been calculated using the formula above and is represented in Figure 6.5.

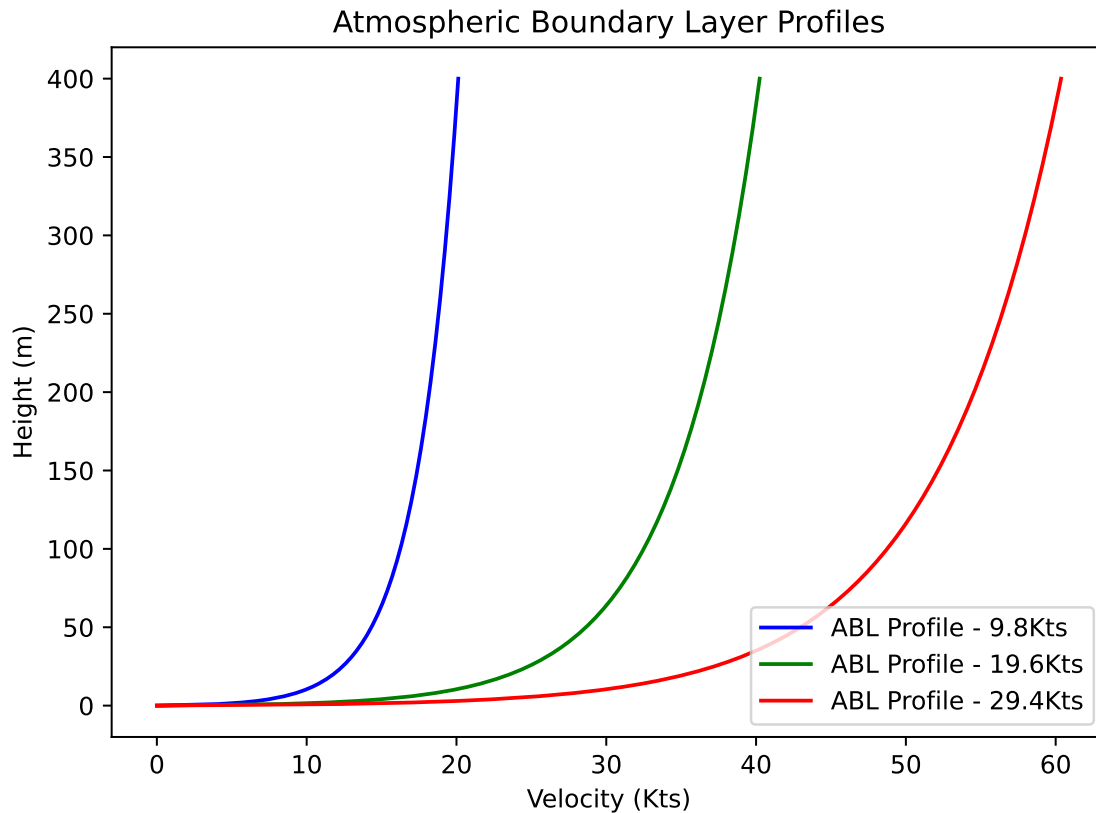


Figure 6.5: Wind Profiles Used in the Model

7. CONCLUSION of ANALYSIS

This chapter reports the summary of the analysis carried out, showing the wind shear and turbulence impact of the proposed development on each of the runway. Details of the CFD simulations and calculations that were used to elaborate the summaries can be found in Appendix A 'CFD Results'. Details of the verification and validation of the method used in this study are presented in Appendix B.

7.1 IMPACT ON RUNWAY 23L/05R

As shown in section 4.2, the proposed Atlas Business Park Development is not located within the trigger area of runway 23L/05R suggested by the NLR report or the NASF guideline. Hence, no further analysis is required in relation to Runway 23R/05L as the proposed development, in accordance with the above guidelines does not pose a wind shear and turbulence risk for this runway.

7.2 IMPACT ON RUNWAY 23R/05L

As shown in section 4.2, the proposed Atlas Business Park Development is located within the NLR assessment trigger area and the distance from the runway 23R/05L extended centerline to the closest point of the development is around 22 m which is less than 35 times the height of the development (Figure 7.1). Therefore, as discussed in section 2.3 ('Acceptance criteria') the basis of regulatory control study, requires the adoption of along-wind and across-wind velocity criteria, and the adoption of a turbulence criterion, that are implemented on Runway 23R/05L by using CFD technique.

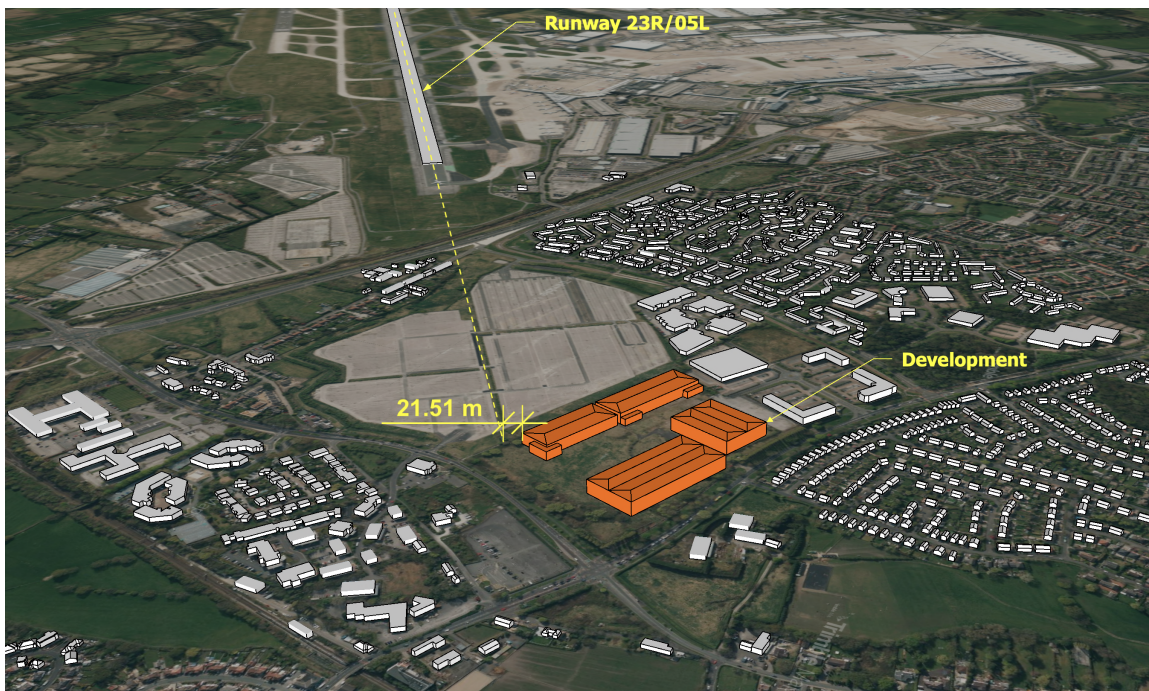


Figure 7.1: Development Relative to Runway 23R/05L

7.2.1 7 Knot along-wind criterion

Figure 7.2 relates the mean velocity deficit obtained for each different aircraft trajectory paths (the variables collected for the calculation of the mean velocity deficit are detailed in Appendix A) with the approaching wind speed.

As it can be seen from Figure 7.2, for approaching wind speed 5m/s (9.8 Kts), 10m/s (19.4 Kts) and 15 m/s (29.2 Kts), the NLR "7 Knot criterion" is never exceeded.

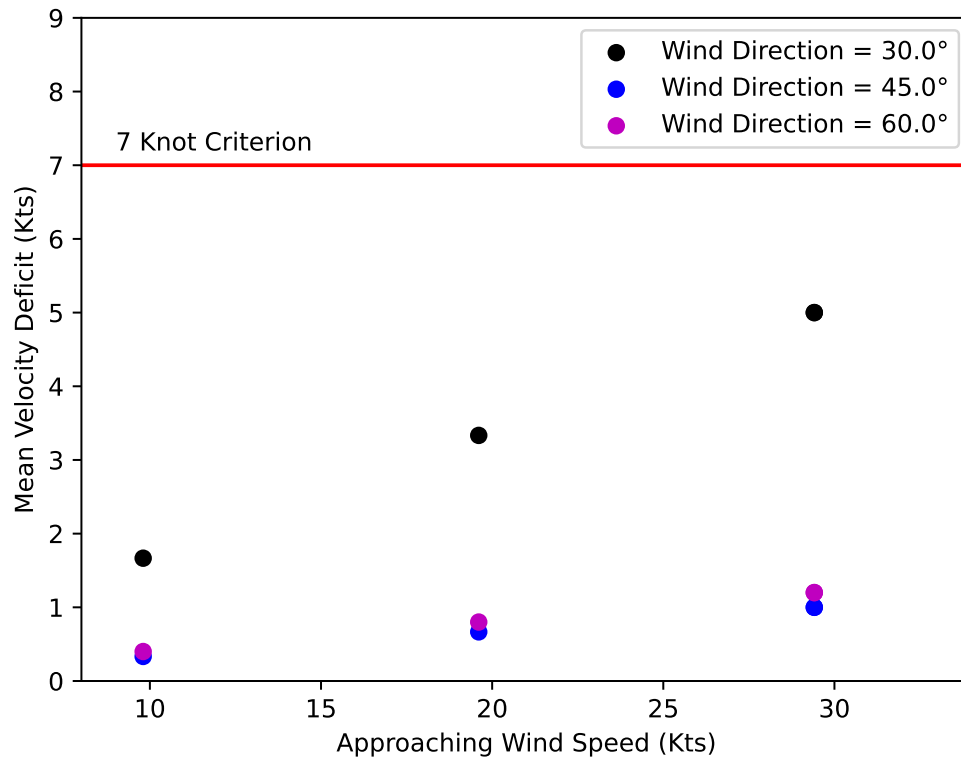


Figure 7.2: Mean Velocity Deficit Exceedance Occurrence - 7 Knot Along-Wind Criterion

7.2.2 6 Knot across-wind criterion

Figure 7.3 relates the mean velocity deficit obtained for each different aircraft trajectory paths (the variables collected for the calculation of the mean velocity deficit are detailed in Appendix A) with the approaching wind speed.

As it can be seen from Figure 7.3, for approaching wind speed 5m/s (9.8 Kts), 10m/s (19.4 Kts) and 15 m/s (29.2 Kts), the NLR "6 Knot criterion" is never exceeded.

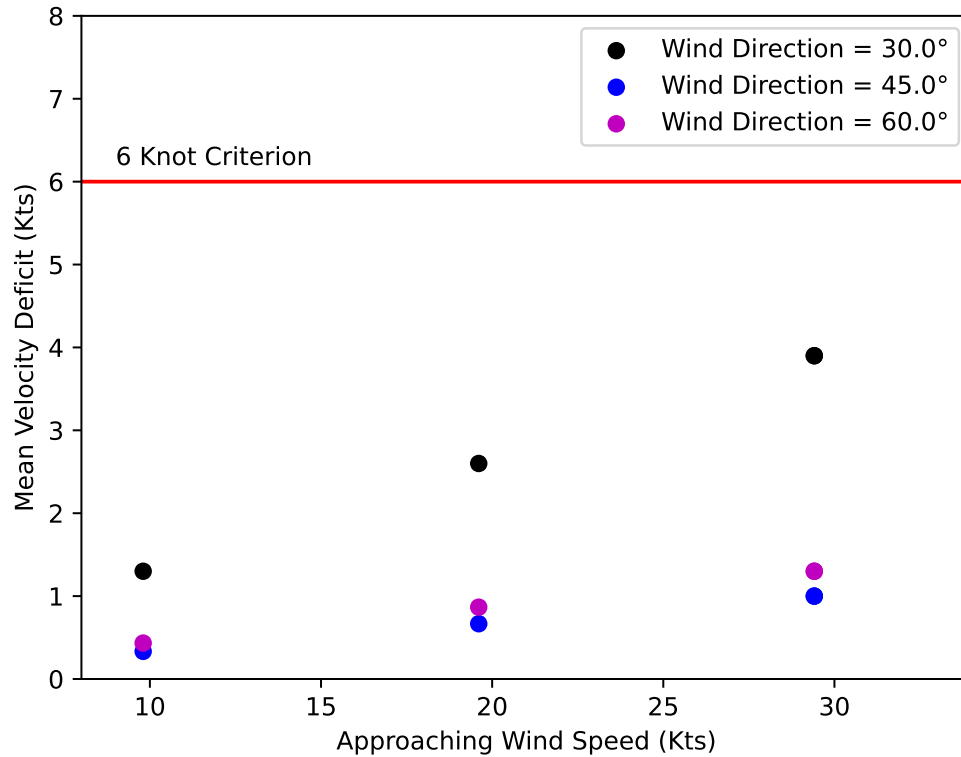


Figure 7.3: Mean Velocity Deficit Exceedance Occurrence - 6 Knot Across-Wind Criterion

7.2.3 4 Knot turbulence criterion

Figure 7.4 relates the turbulence deviation obtained for each different aircraft trajectory paths (the variables collected for the calculation of the mean velocity deficit are detailed in Appendix A) with the approaching wind speed.

As it can be seen from Figure 7.4, for approaching wind speed 5m/s (9.8 Kts), 10m/s (19.4 Kts) and 15 m/s (29.2 Kts), the NLR "4 Knot criterion" is never exceeded.

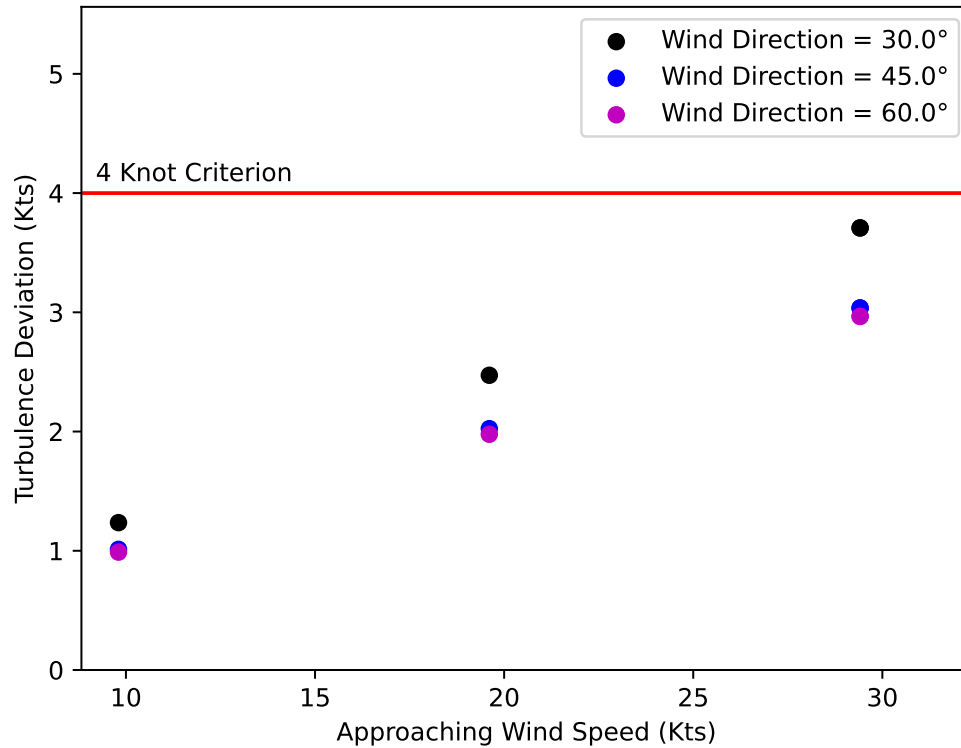


Figure 7.4: Max Turbulence Deviation (RMS) in Knot Exceedance Occurrence - 4 Knot Turbulence Criterion

8. REFERENCES

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APPENDIX A: CFD RESULTS

This chapter shows the CFD results of the wind assessment. Sample results of CFD models along runway 23R/05L and 10m above ground level based on the following wind conditions:

- approach wind speeds are 5m/s (9.8 Kts), 10m/s (19.4 Kts) and 15m/s (29.2 Kts).
- approach wind directions are 30°, 45° and 60°.

Flow Velocity and Turbulence Results:

Results of velocity along runway 23R/05L and 10m above the ground are presented in Figures 1 to 18.

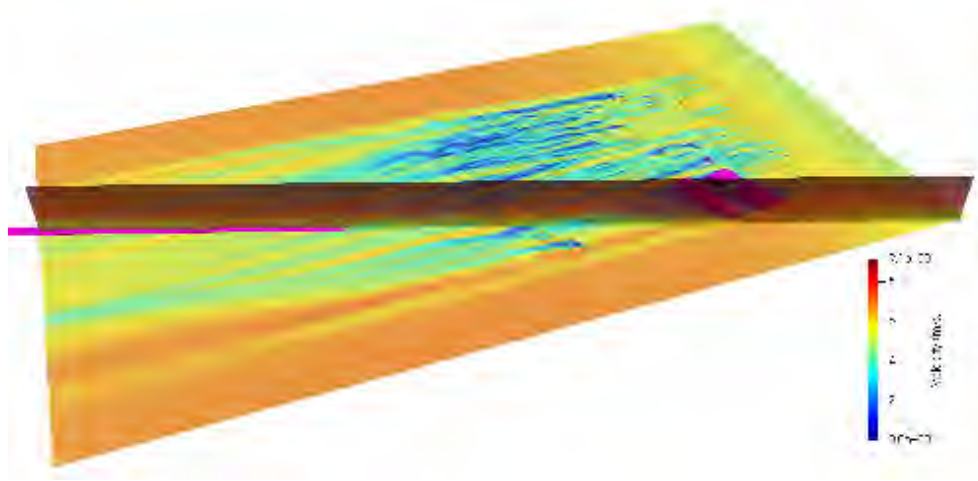


Figure 1: Flow Velocity Results at Z=10m above the ground and along runway 23R/05L - Reference wind speed 5 (m/s) - Wind Direction: 30°

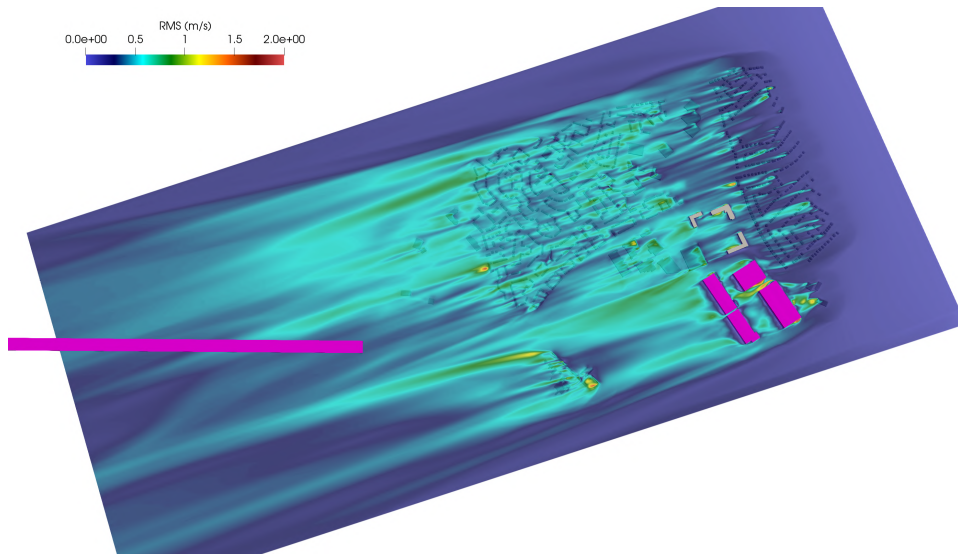


Figure 2: Turbulence Deviation Results at Z=10m above the ground - Reference Wind Speed 5 (m/s) - Wind Direction: 30°

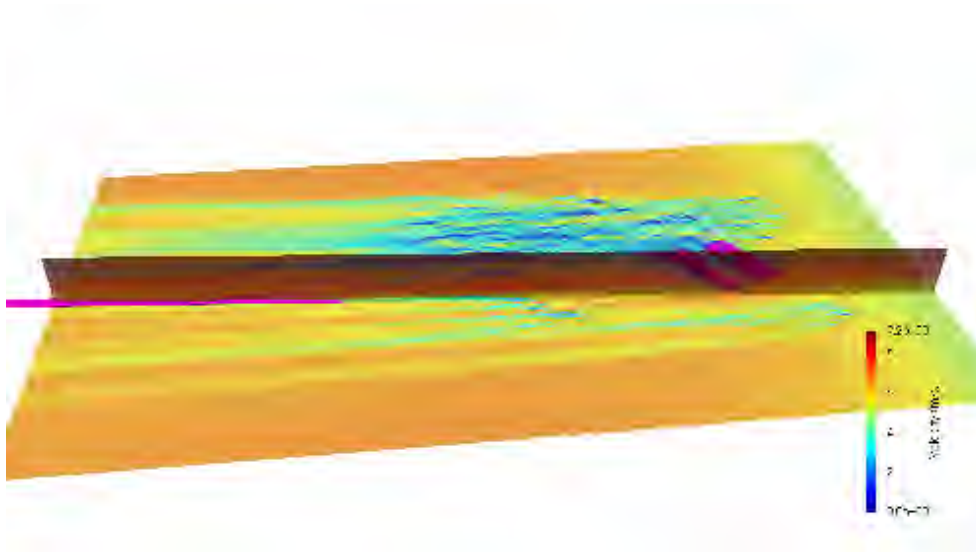


Figure 3: Flow Velocity Results at Z=10m above the ground and along runway 23R/05L - Reference wind speed 5 (m/s) - Wind Direction: 45°

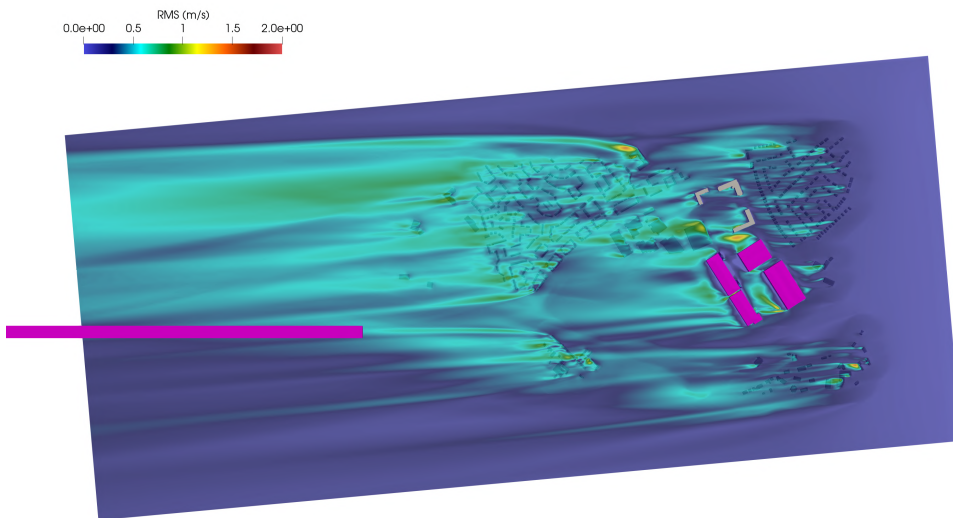


Figure 4: Turbulence Deviation Results at Z=10m above the ground - Reference Wind Speed 5 (m/s) - Wind Direction: 45°

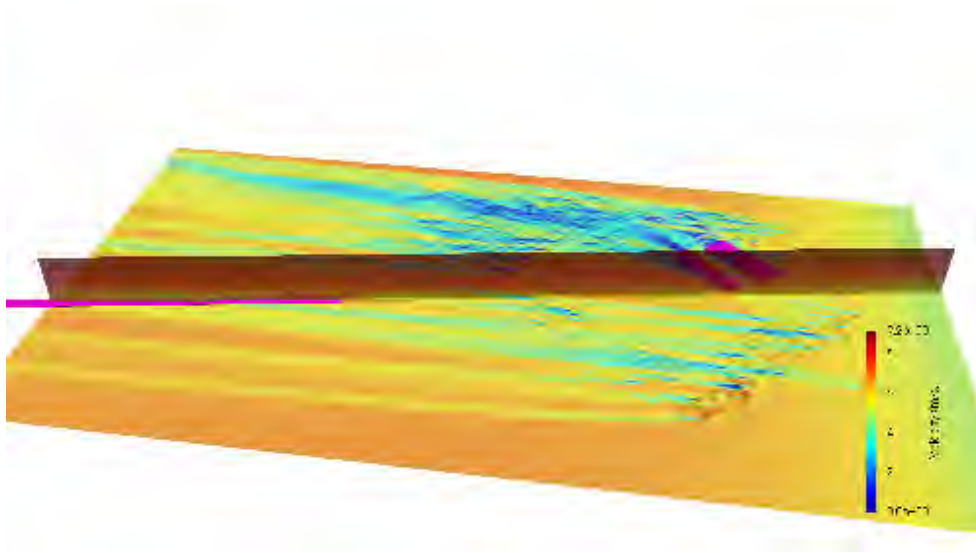


Figure 5: Flow Velocity Results at $Z=10\text{m}$ above the ground and along runway 23R/05L - Reference wind speed 5 (m/s) - Wind Direction: 60°

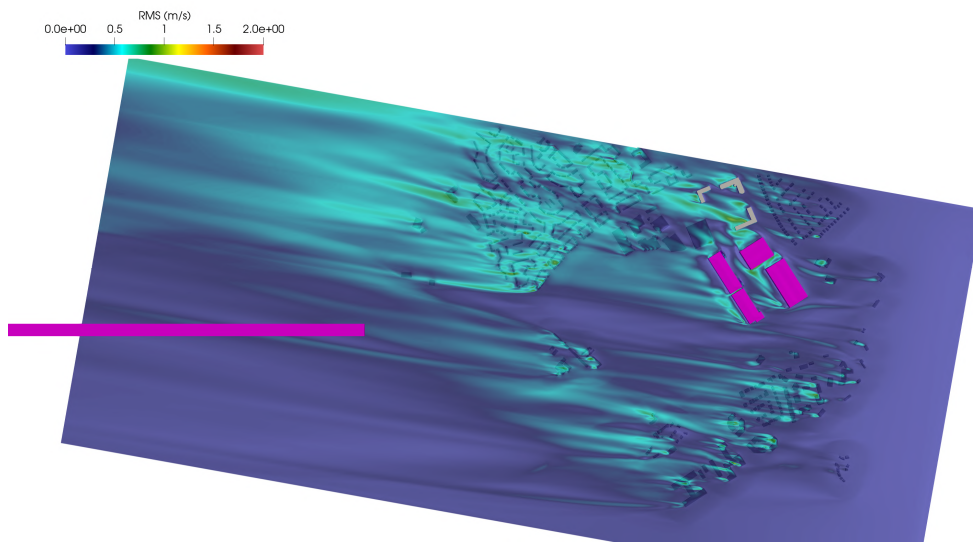


Figure 6: Turbulence Deviation Results at $Z=10\text{m}$ above the ground - Reference Wind Speed 5 (m/s) - Wind Direction: 60°

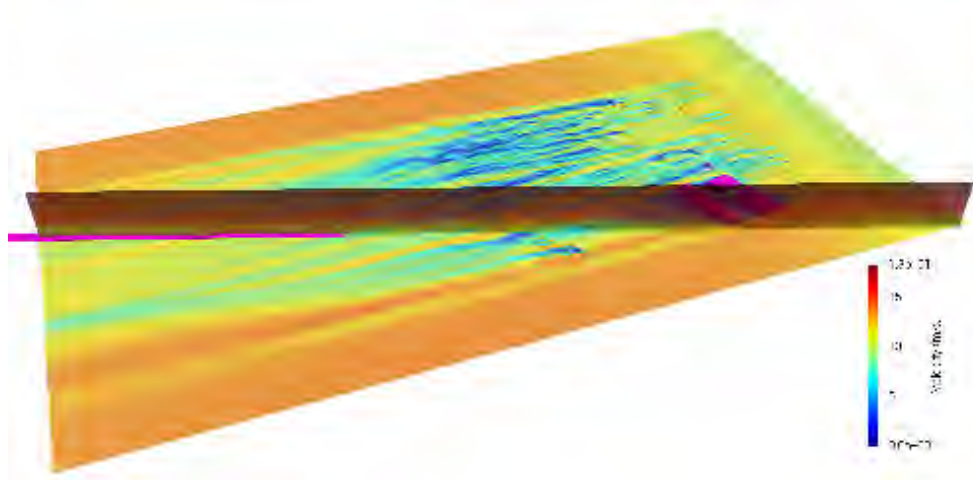


Figure 7: Flow Velocity Results at Z=10m above the ground and along runway 23R/05L - Reference wind speed 10 (m/s) - Wind Direction: 30°

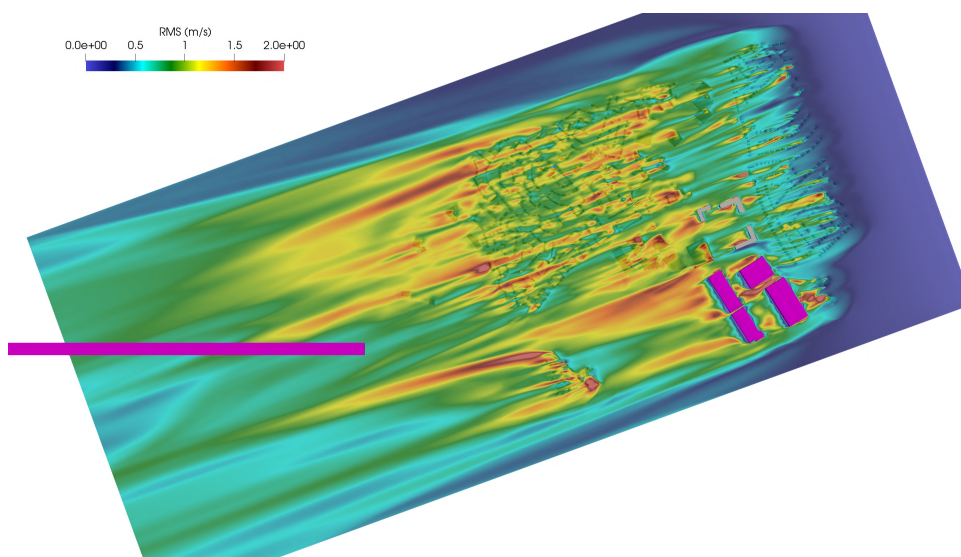


Figure 8: Turbulence Deviation Results at Z=10m above the ground - Reference Wind Speed 10 (m/s) - Wind Direction: 30°

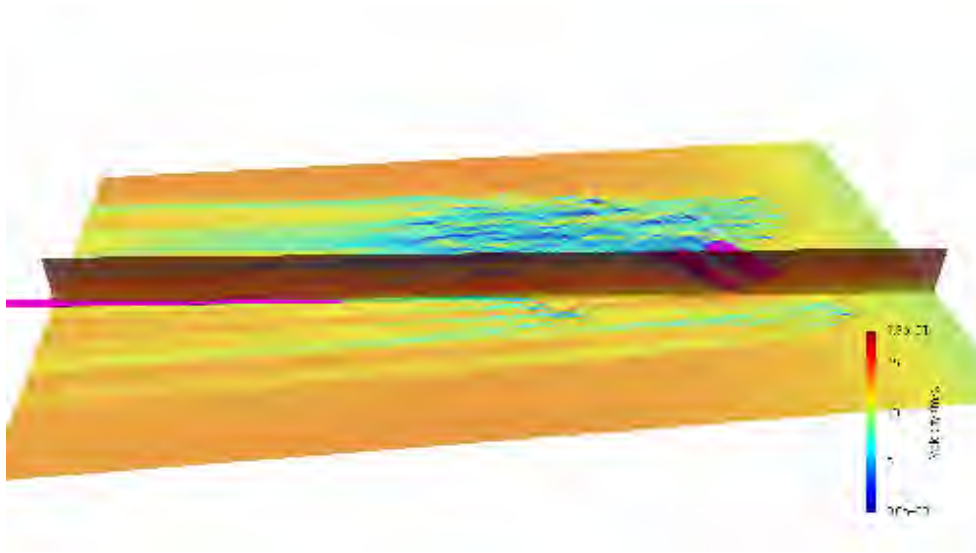


Figure 9: Flow Velocity Results at $Z=10\text{m}$ above the ground and along runway 23R/05L - Reference wind speed 10 (m/s) - Wind Direction: 45°

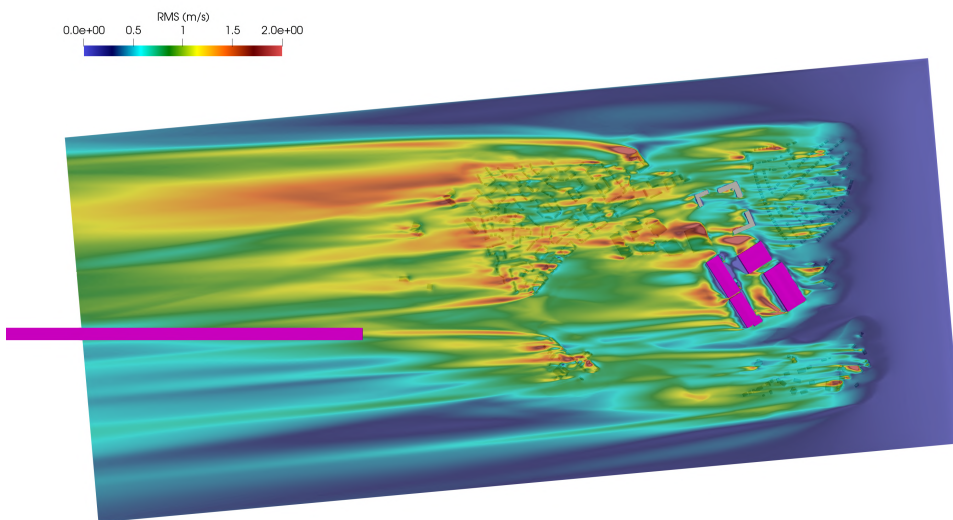


Figure 10: Turbulence Deviation Results at $Z=10\text{m}$ above the ground - Reference Wind Speed 10 (m/s) - Wind Direction: 45°

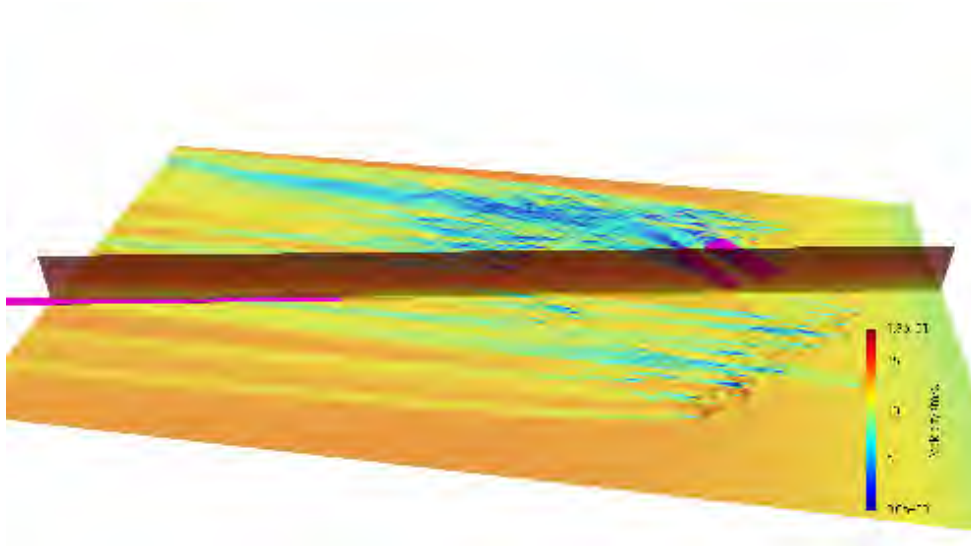


Figure 11: Flow Velocity Results at Z=10m above the ground and along runway 23R/05L - Reference wind speed 10 (m/s) - Wind Direction: 60°

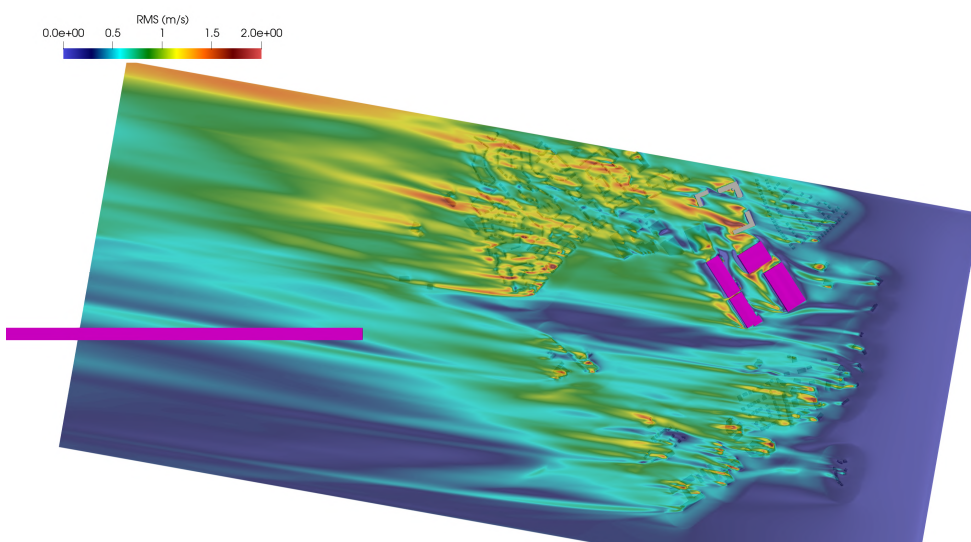


Figure 12: Turbulence Deviation Results at Z=10m above the ground - Reference Wind Speed 10 (m/s) - Wind Direction: 60°

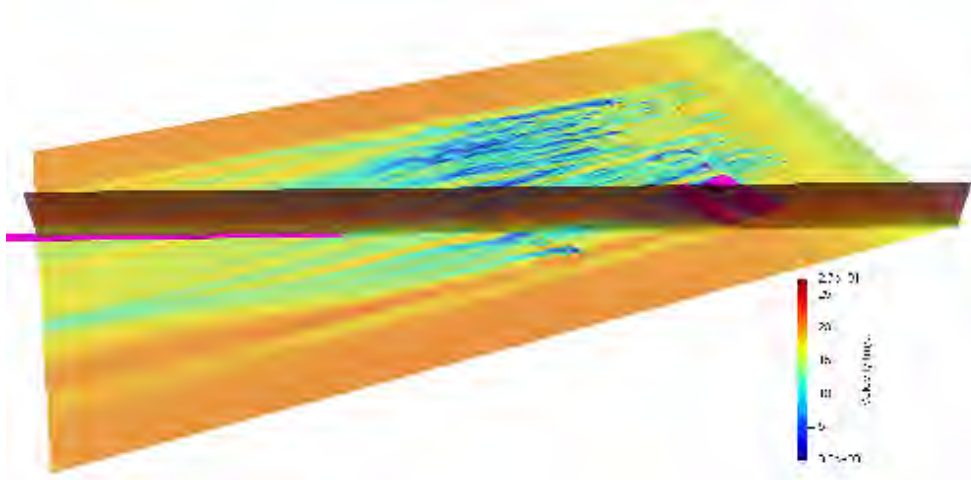


Figure 13: Flow Velocity Results at Z=10m above the ground and along runway 23R/05L - Reference wind speed 15 (m/s) - Wind Direction: 30°

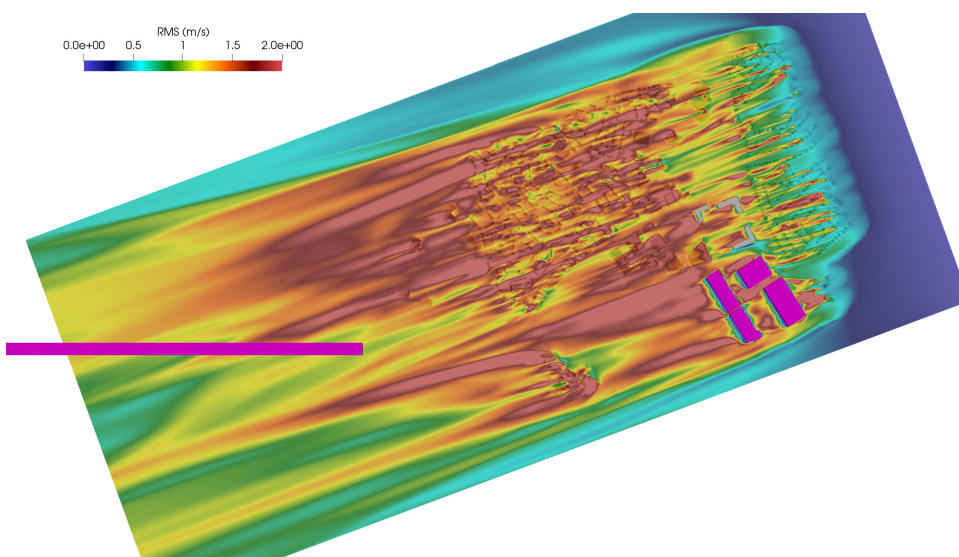


Figure 14: Turbulence Deviation Results at Z=10m above the ground - Reference Wind Speed 15 (m/s) - Wind Direction: 30°

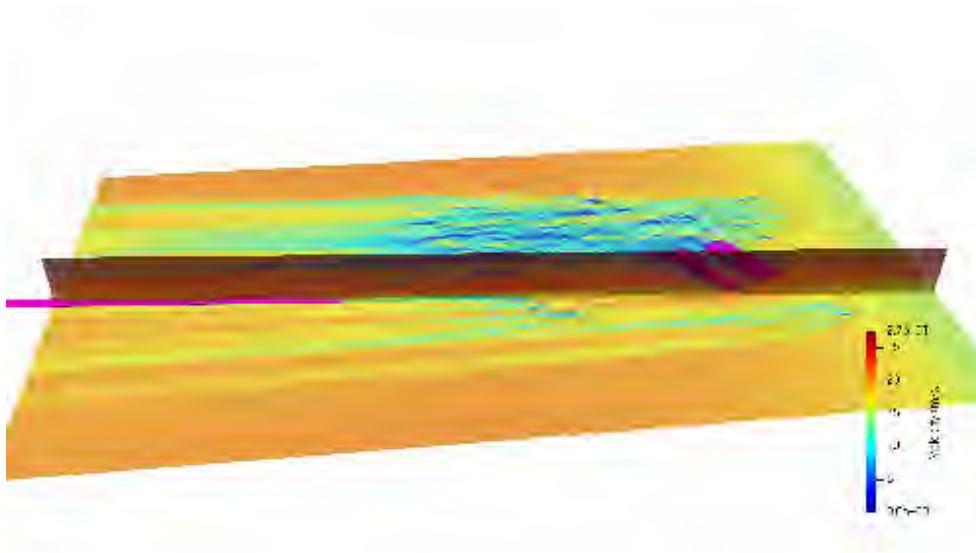


Figure 15: Flow Velocity Results at Z=10m above the ground and along runway 23R/05L - Reference wind speed 15 (m/s) - Wind Direction: 45°

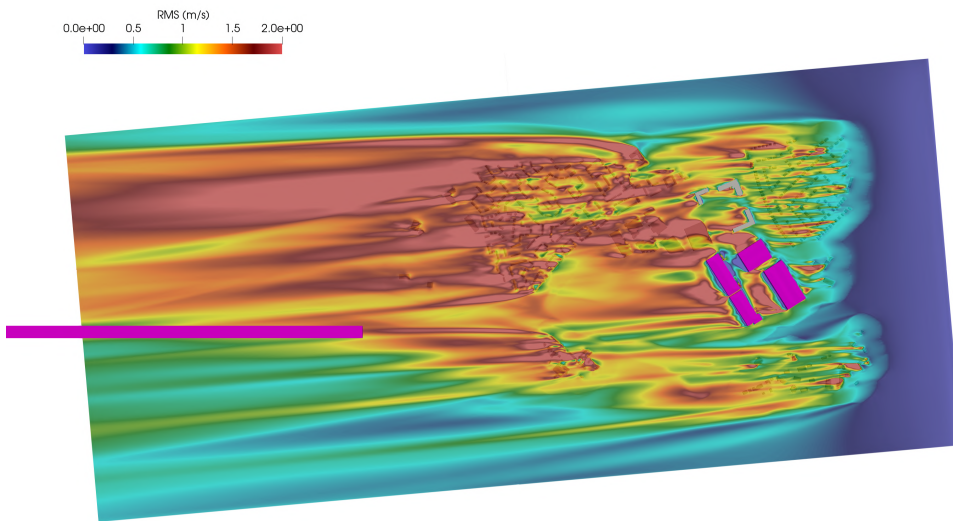


Figure 16: Turbulence Deviation Results at Z=10m above the ground - Reference Wind Speed 15 (m/s) - Wind Direction: 45°

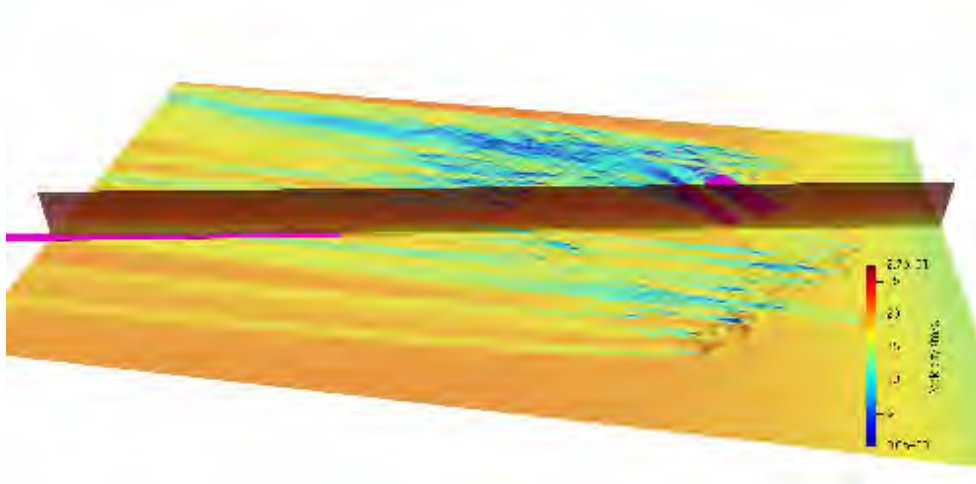


Figure 17: Flow Velocity Results at $Z=10\text{m}$ above the ground and along runway 23R/05L - Reference wind speed 15 (m/s) - Wind Direction: 60°

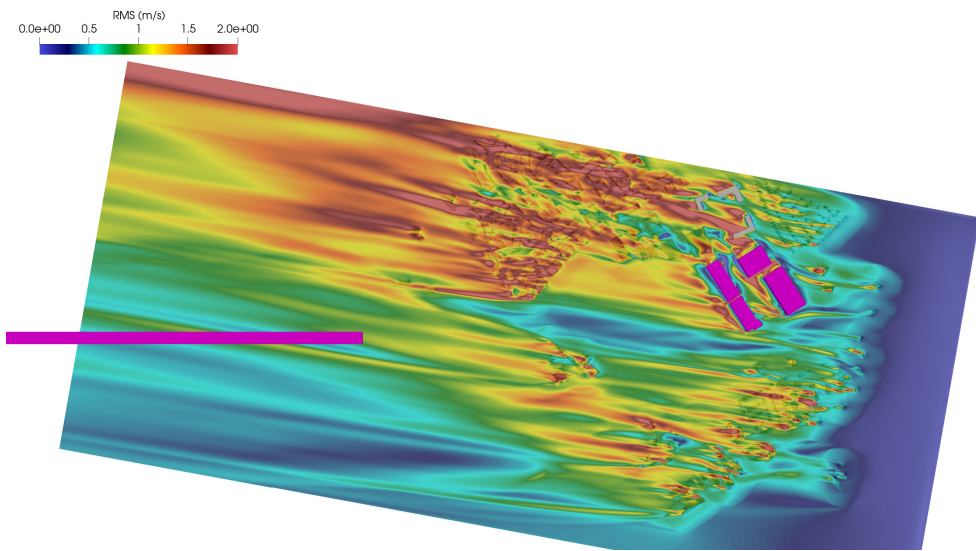


Figure 18: Turbulence Deviation Results at $Z=10\text{m}$ above the ground - Reference Wind Speed 15 (m/s) - Wind Direction: 60°

Possible Landing Scenarios:

In the wind shear and turbulence modelling study, wind speed and turbulence must be reported at the aircraft trajectory. The approaching angle for landing is usually between 2.7° and 4° , with 3° considered as the average.

In this study, 3° and 4° landing/takeoff degrees are analysed. It is assumed that the aircraft glides down with constant speed and its track angle is either 3° or 4° .

Figure 19 shows a schematic of the first two criteria suggested by the NLR study. The 6-kt and 7-kt criteria are associated with the maximum change in mean wind speed in the cross-flight and along-flight directions respectively relates to a 100m distance along the glide path.

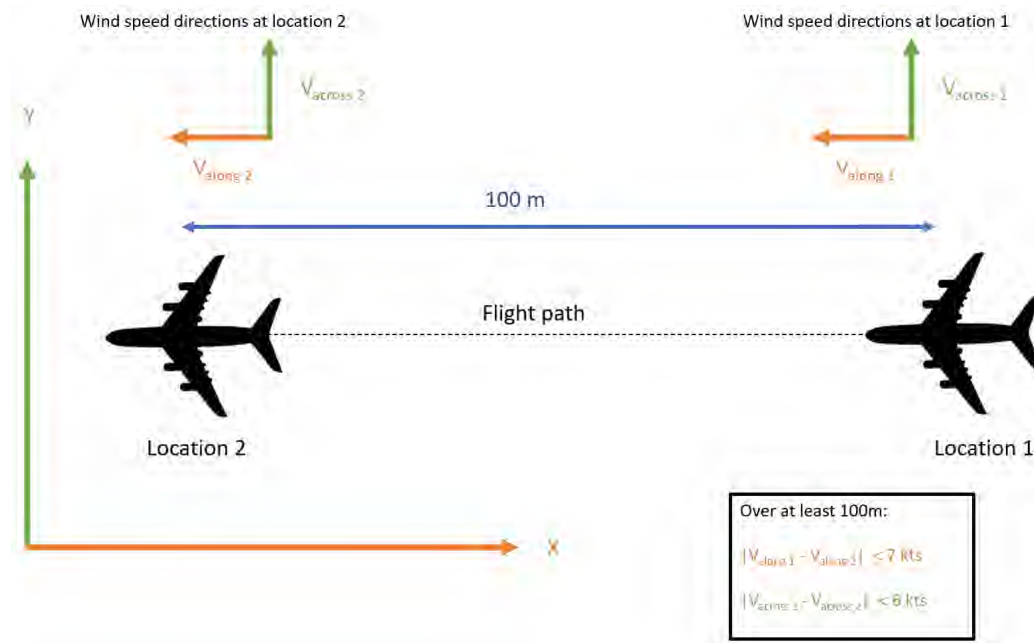


Figure 19: Schematic of NLR criteria

Six possible paths per each landing degrees are considered. Each path starts at 1200m far from touch down zone and continues to ground level. Fluid velocity and turbulence values are collected along each path. In addition, every 100m across each possible aircraft trajectory, data sampling were performed per each landing path. The sample values are interpolated from values between the cellpoints. Landing paths and horizontal sampling lines are shown in Figures from 20 to 22.

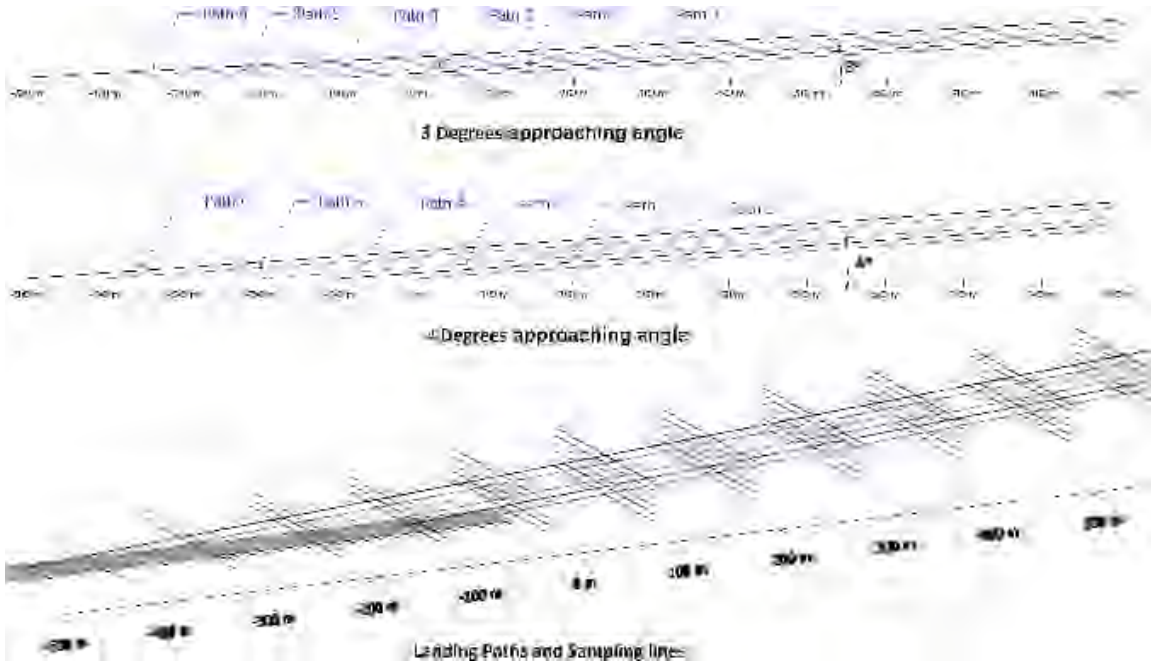


Figure 20: Landing Scenarios and Sampling lines at 3° and 4° approaching angle

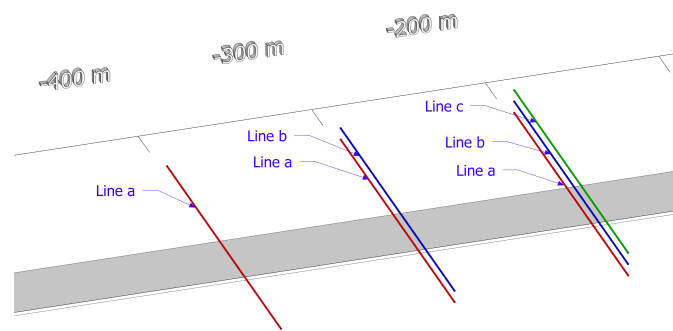


Figure 21: Sampling lines perpendicular to possible critical aircraft trajectories at 3° or 4° approaching angle



Figure 22: Sampling lines perpendicular to a possible critical aircraft trajectories at 3° or 4° approaching angle

Reference Wind Speed at 10m above ground = 5m/s
Wind Direction = 30°

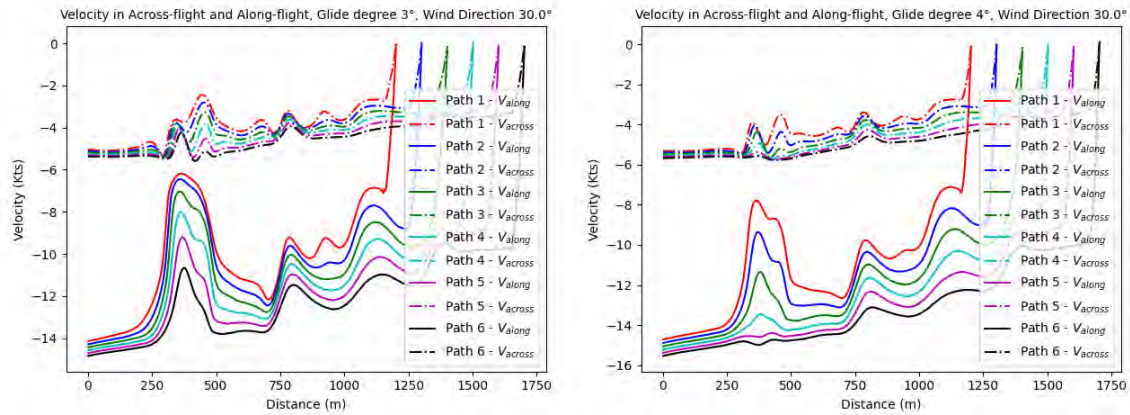


Figure 23: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 5 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 30°

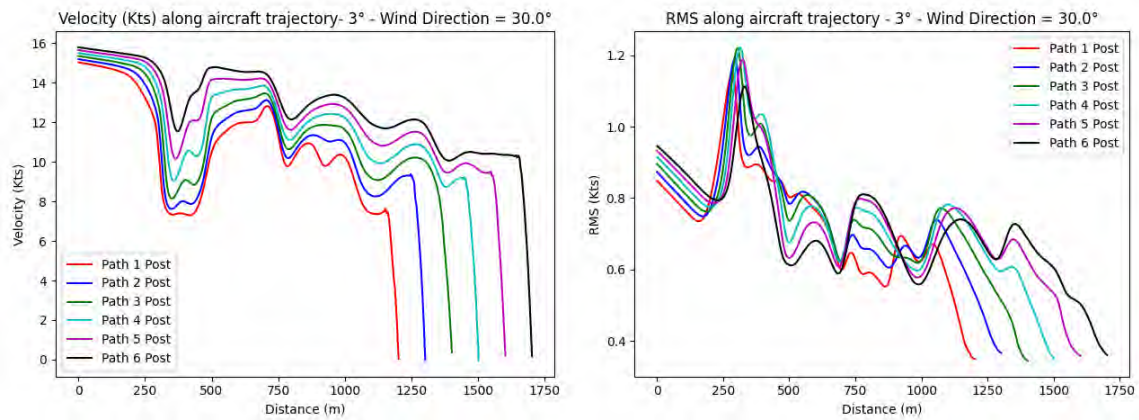


Figure 24: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 5(m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

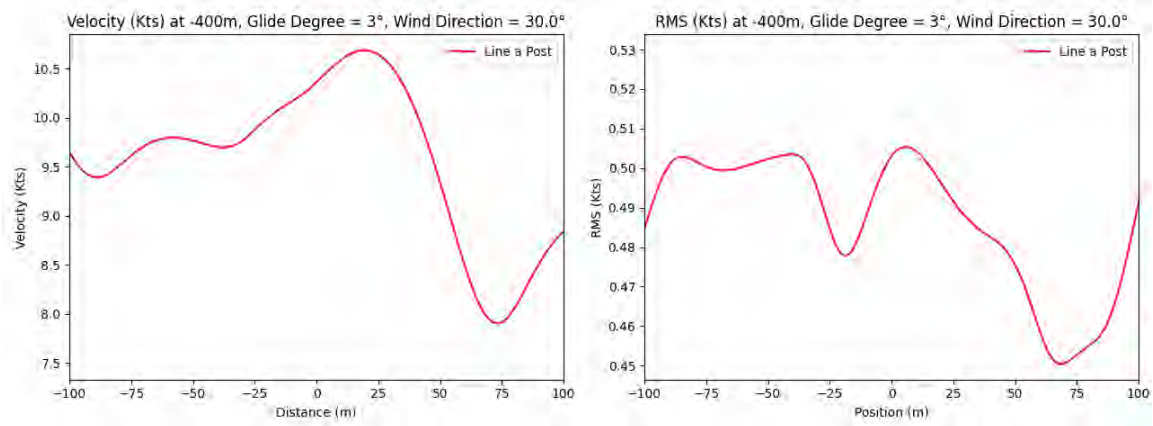


Figure 25: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

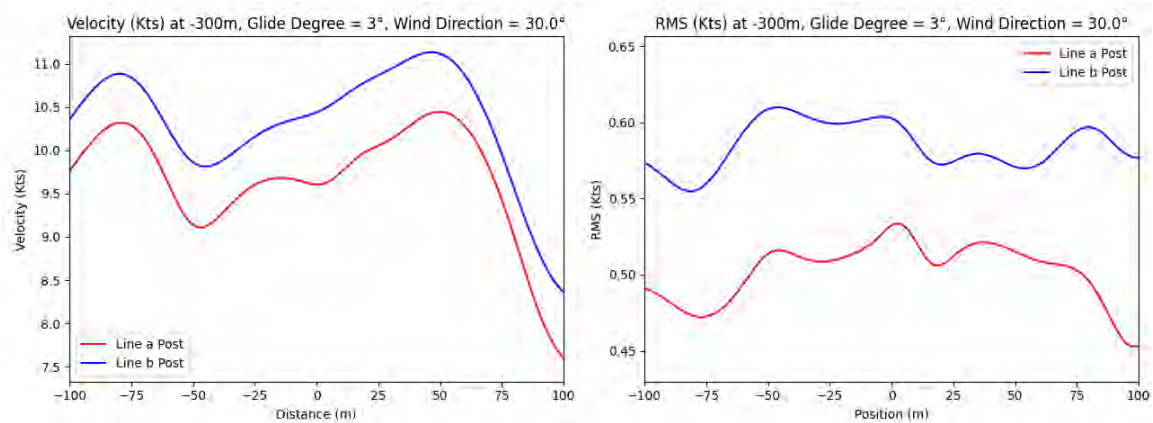


Figure 26: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

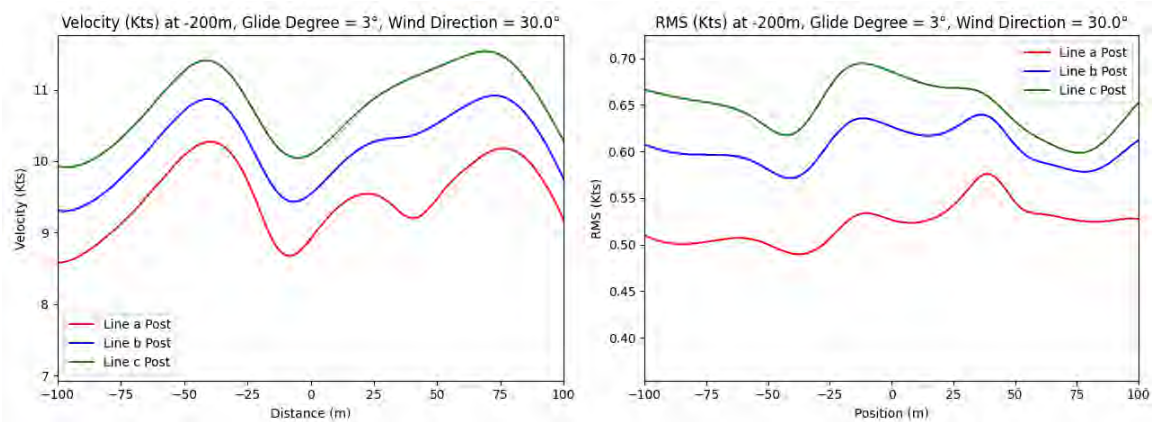


Figure 27: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

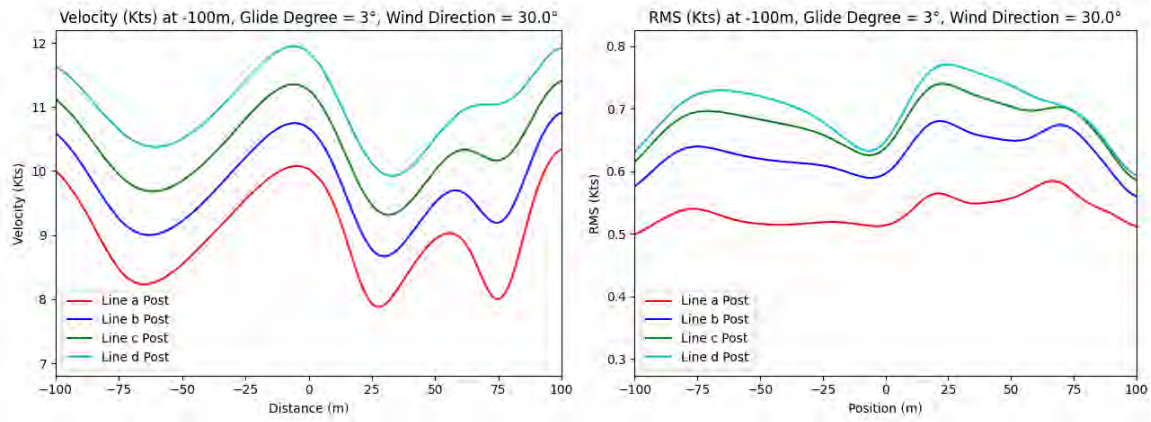


Figure 28: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

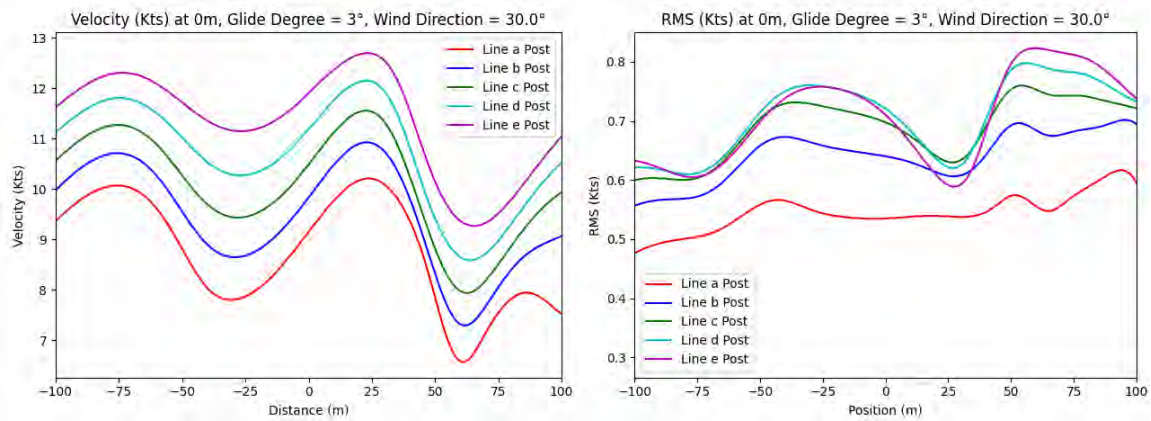


Figure 29: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

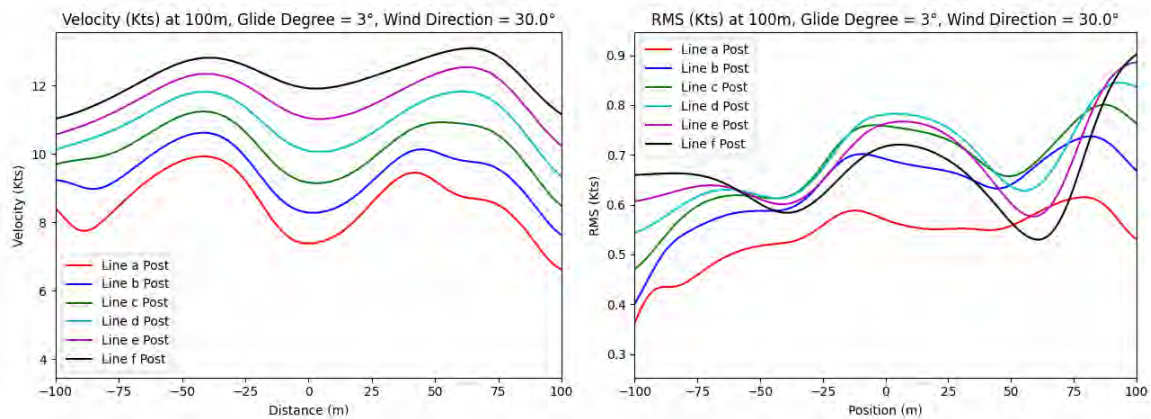


Figure 30: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

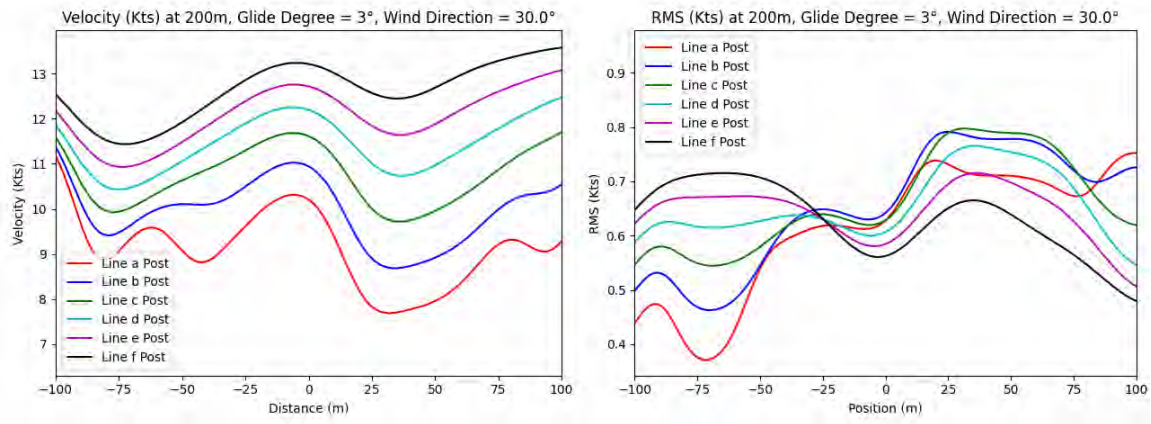


Figure 31: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

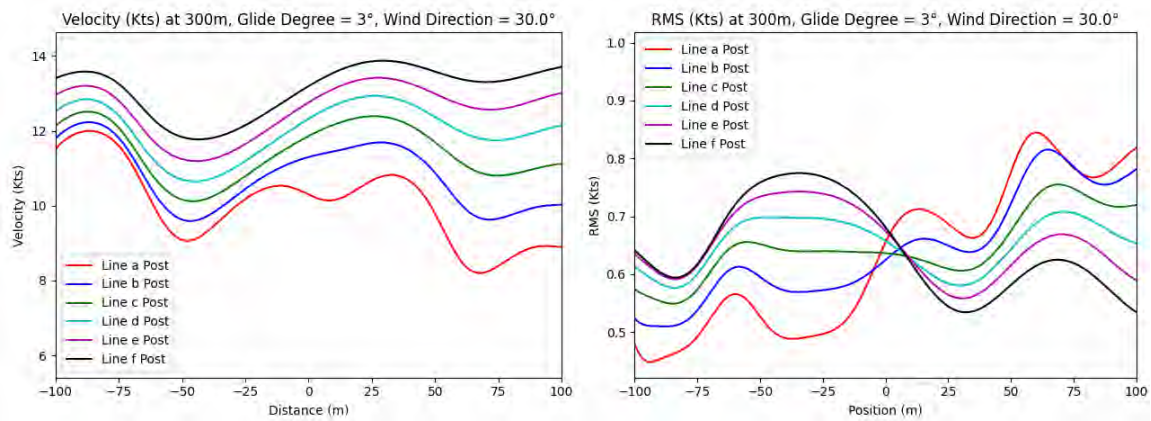


Figure 32: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

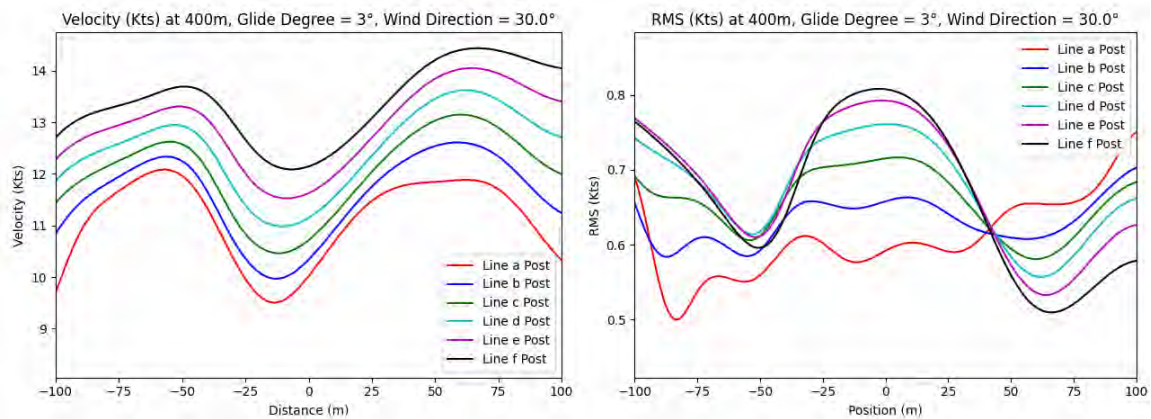


Figure 33: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

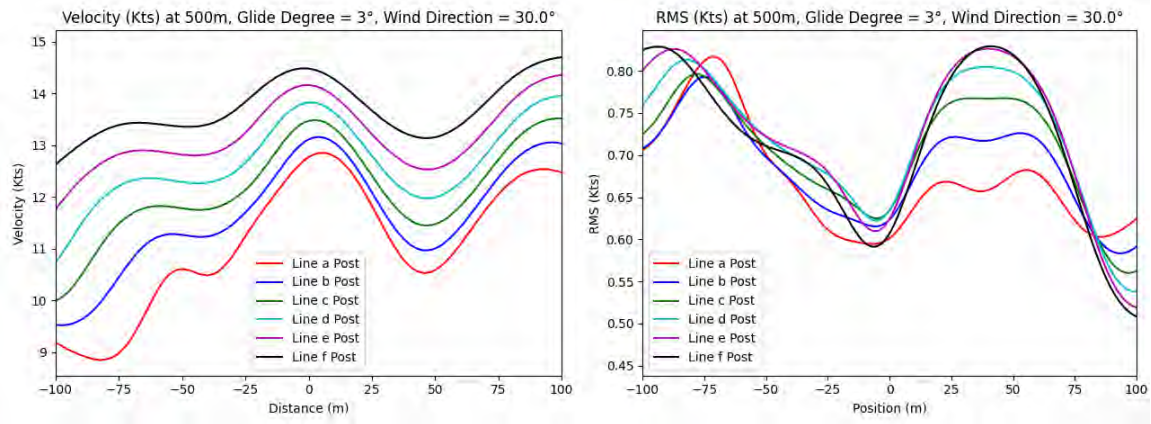


Figure 34: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

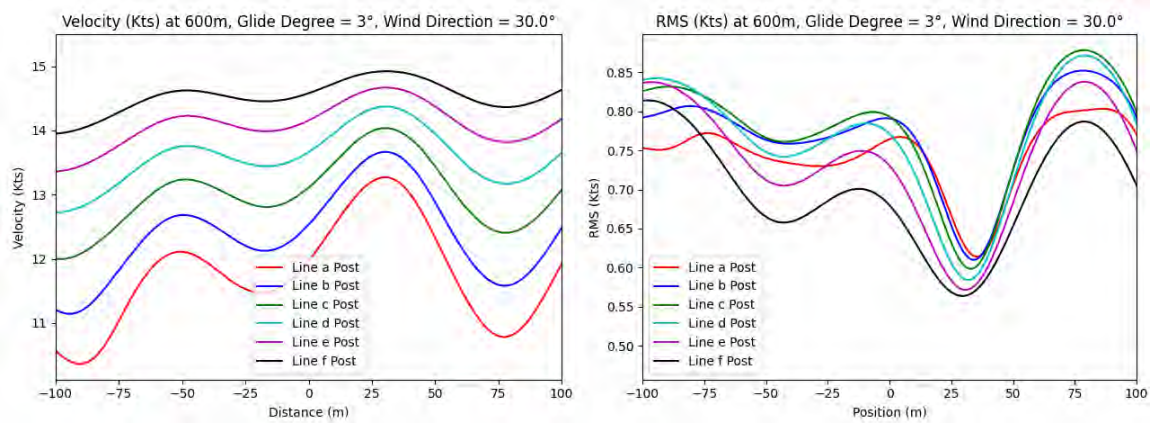


Figure 35: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

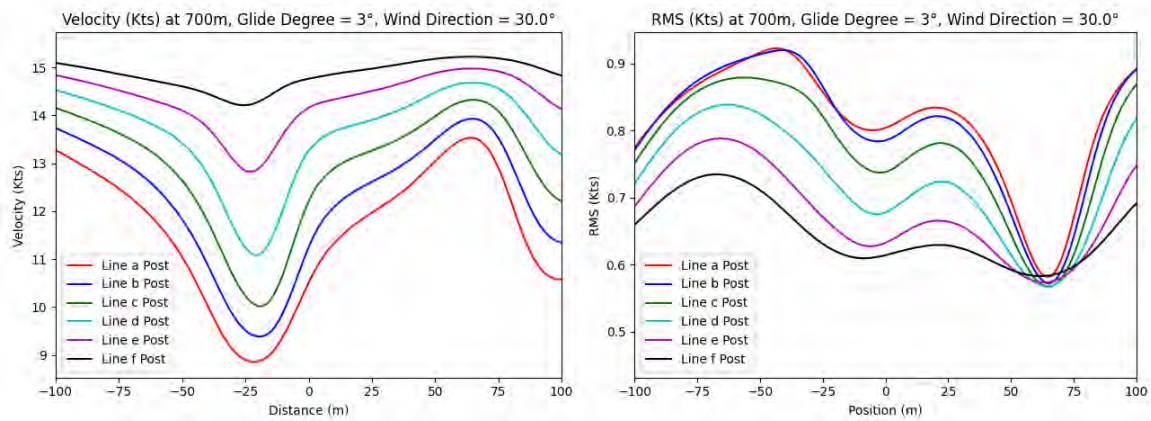


Figure 36: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

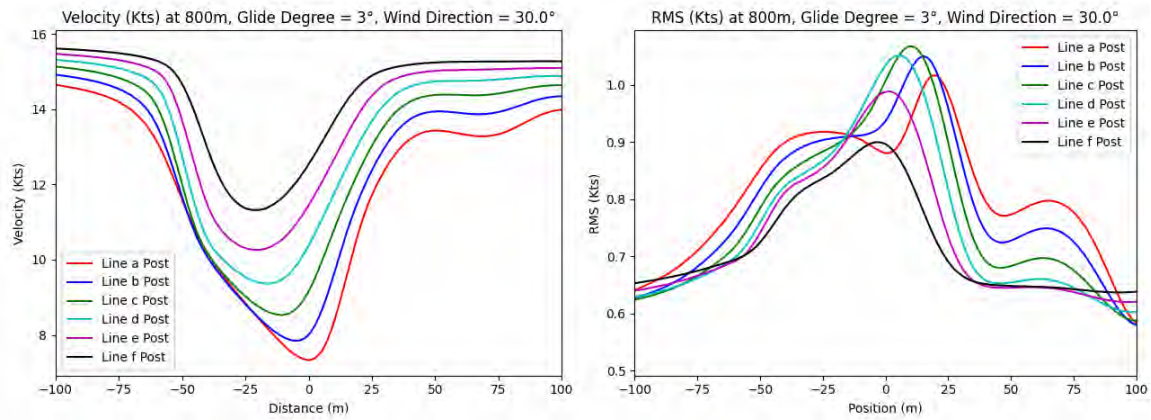


Figure 37: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

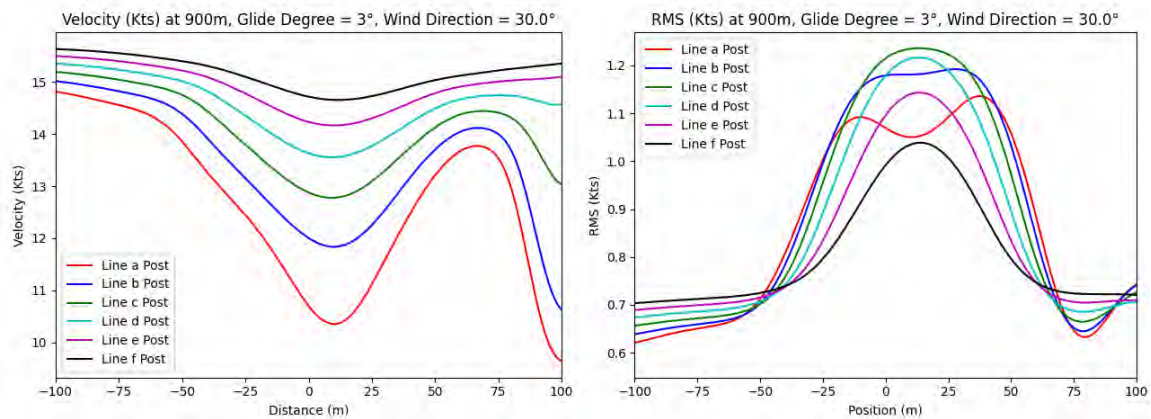


Figure 38: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 30° with 5 m/s approaching speed are shown in tables 1 and 2.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	14.68	14.96	14.82	14.7	15	15.02	14.9	14.96	14.64	13.62	14.91	14.77	14.43	10.91	13.29
55	14.31	14.71	14.5	14.26	14.73	14.74	14.56	14.68	14.24	12.97	14.63	14.38	13.73	9.74	12.48
50	13.93	14.45	14.16	13.79	14.45	14.42	14.15	14.36	13.85	12.44	14.34	13.94	12.78	8.54	11.53
45	13.55	14.15	13.79	13.26	14.12	14.03	13.66	13.97	13.44	11.93	14.03	13.44	11.8	7.67	10.01
40	13.17	13.83	13.39	12.71	13.73	13.56	13.1	13.53	13.03	11.45	13.69	12.9	10.96	7.23	8.75
35	12.8	13.47	12.97	12.17	13.3	13.01	12.45	13.06	12.61	11	13.35	12.34	10.31	7.07	8.27
30	12.44	13.07	12.52	11.63	12.82	12.4	11.7	12.59	12.19	10.6	13.01	11.81	9.81	7.06	8.12
25	12.1	12.64	12.04	11.09	12.31	11.73	10.84	12.08	11.74	10.25	12.68	11.31	9.39	7.13	8.19
20	11.76	12.15	11.54	10.55	11.76	11.04	9.92	11.5	11.17	9.95	12.4	10.86	9.01	7.23	8.42
15	11.42	11.63	10.99	10.02	11.19	10.38	9.04	10.85	10.1	9.72	12.16	10.48	8.68	7.31	8.75
10	11.07	11.04	10.37	9.48	10.62	9.76	8.21	10.15	8.11	9.53	11.95	10.16	8.41	7.36	9.12
5	10.59	10.31	9.56	8.88	10	9.1	7.35	9.41	6.73	9.3	11.69	9.86	8.21	7.31	9.46

Table 1: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 30°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	0.50066	0.4284	0.48655	0.51921	0.41623	0.43177	0.46722	0.46266	0.60895	0.76052	0.574	0.65461	0.62197	1.01855	1.20432
55	0.54527	0.45411	0.53105	0.58178	0.43579	0.45451	0.49965	0.47837	0.64295	0.79686	0.59465	0.7063	0.65122	1.02749	1.2062
50	0.58311	0.48103	0.57237	0.63794	0.46101	0.48551	0.5386	0.49869	0.66698	0.80846	0.61309	0.75169	0.70371	0.97114	1.13864
45	0.61281	0.50976	0.61035	0.68544	0.49325	0.52755	0.58352	0.52267	0.68032	0.80359	0.6271	0.78363	0.759	0.90855	1.01661
40	0.63259	0.53802	0.64168	0.71919	0.53123	0.57941	0.63127	0.54695	0.68148	0.78298	0.63353	0.79583	0.79437	0.86728	0.92164
35	0.6421	0.56373	0.66417	0.7391	0.57185	0.6358	0.68086	0.56916	0.67125	0.74797	0.63029	0.78525	0.80302	0.8362	0.87666
30	0.64149	0.58505	0.67615	0.7461	0.60921	0.68538	0.73042	0.58986	0.65258	0.70072	0.61722	0.75339	0.78707	0.80228	0.85093
25	0.63086	0.59944	0.67649	0.73932	0.63622	0.71638	0.77007	0.61119	0.63194	0.64364	0.59405	0.70443	0.74903	0.75869	0.82666
20	0.60987	0.60347	0.66453	0.71773	0.64601	0.71973	0.78077	0.63151	0.62471	0.57915	0.5618	0.64203	0.69087	0.70306	0.79374
15	0.57749	0.59259	0.63948	0.67959	0.63232	0.69249	0.75195	0.64125	0.66145	0.50879	0.52081	0.56598	0.61178	0.63382	0.74607
10	0.53122	0.56168	0.59853	0.62019	0.58973	0.63337	0.68361	0.62272	0.64817	0.43049	0.46964	0.47243	0.50827	0.54742	0.67567
5	0.46286	0.49861	0.52679	0.52011	0.5081	0.52822	0.5617	0.55104	0.46575	0.33938	0.40491	0.3483	0.37058	0.42683	0.55609

Table 2: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 30°

Wind Direction = 45°

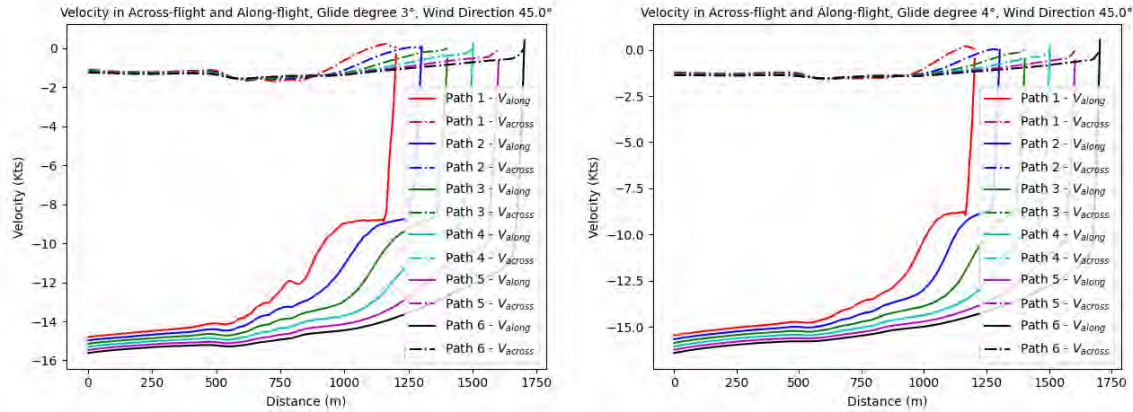


Figure 39: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 5 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 45°

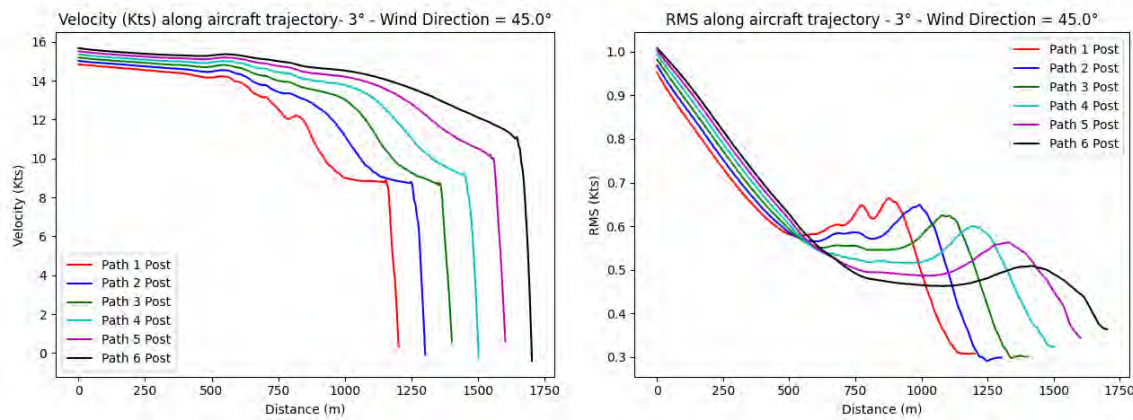


Figure 40: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 5(m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

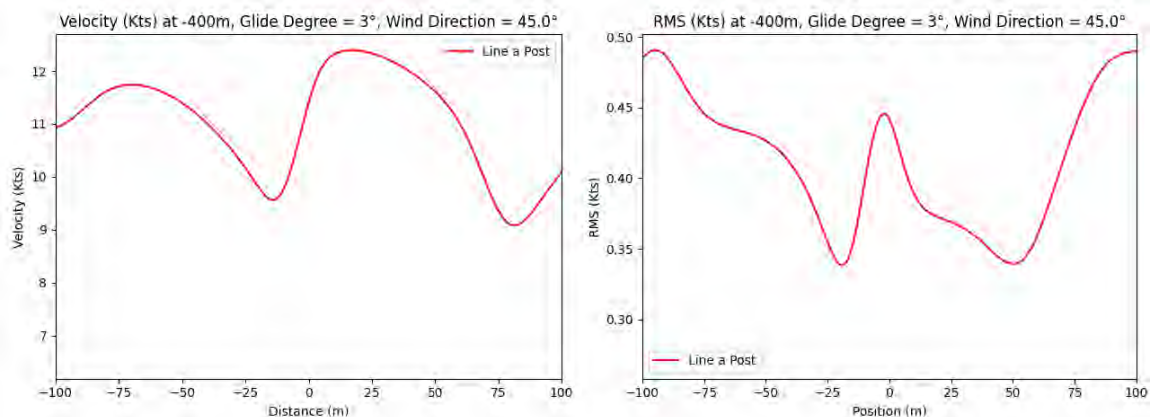


Figure 41: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

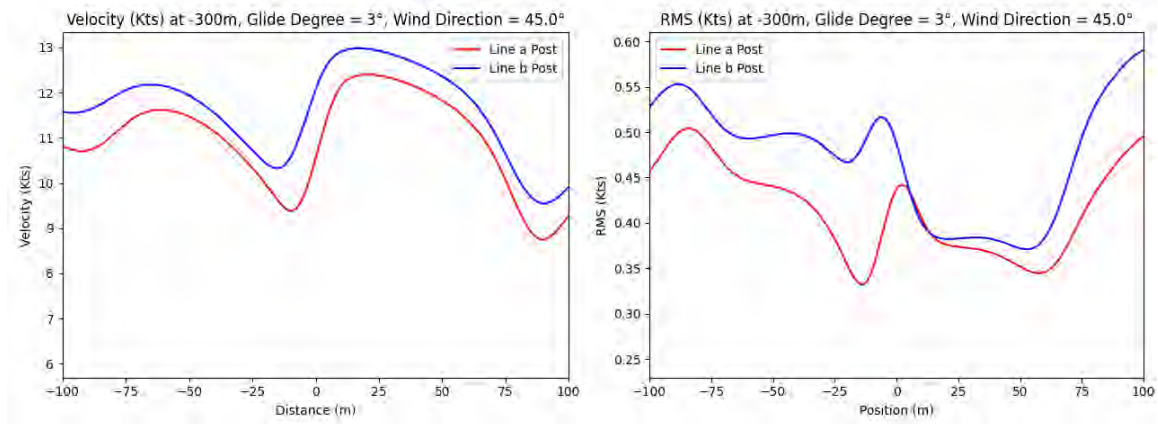


Figure 42: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

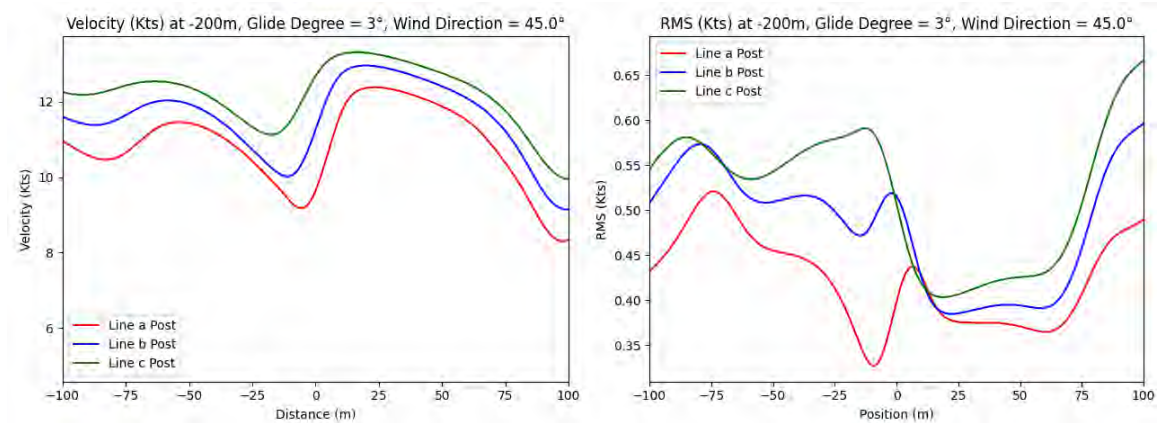


Figure 43: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

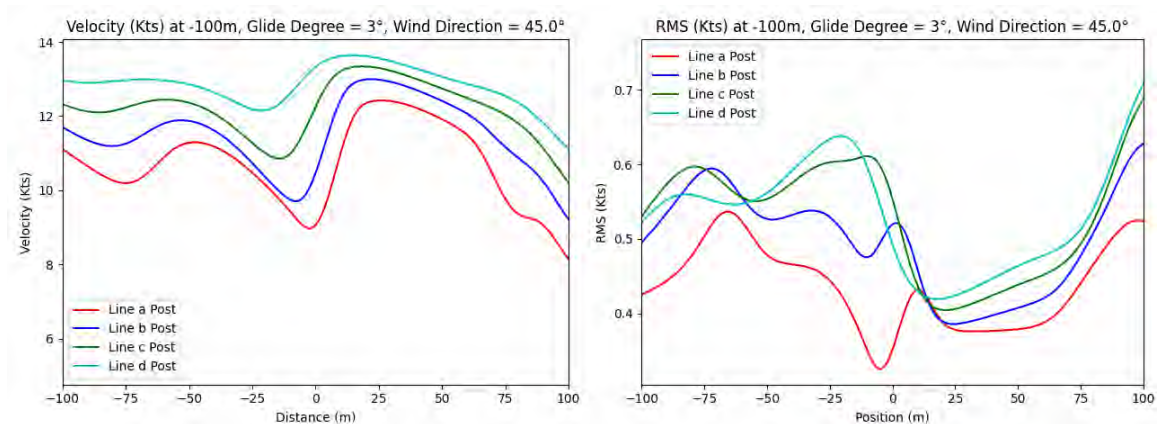


Figure 44: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

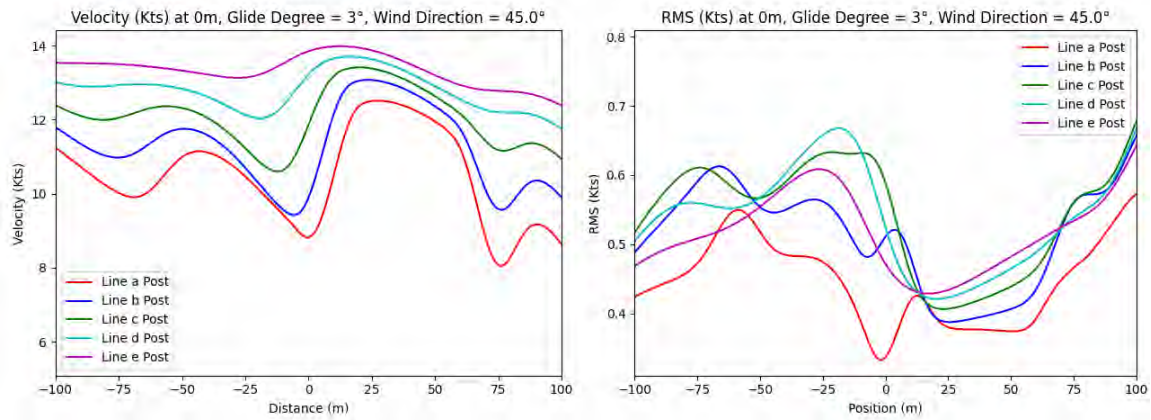


Figure 45: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 45°

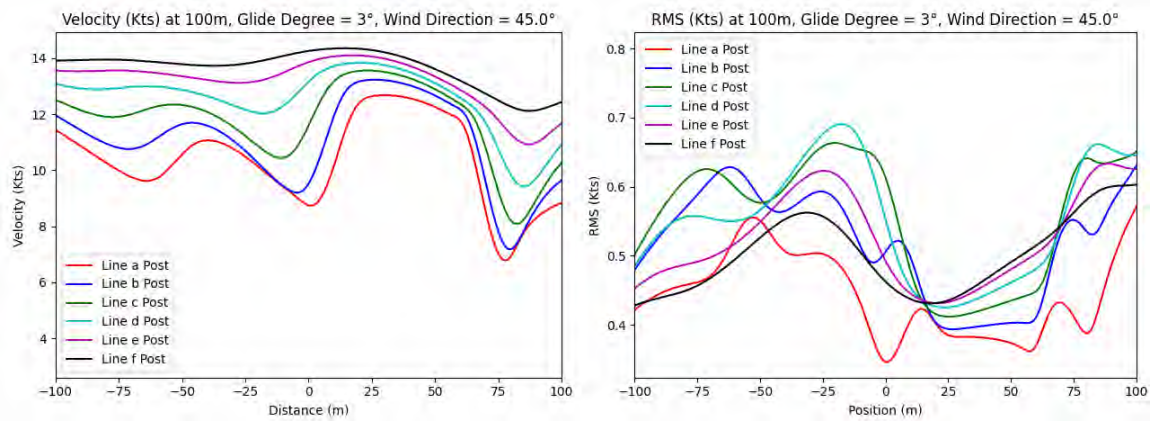


Figure 46: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 45°

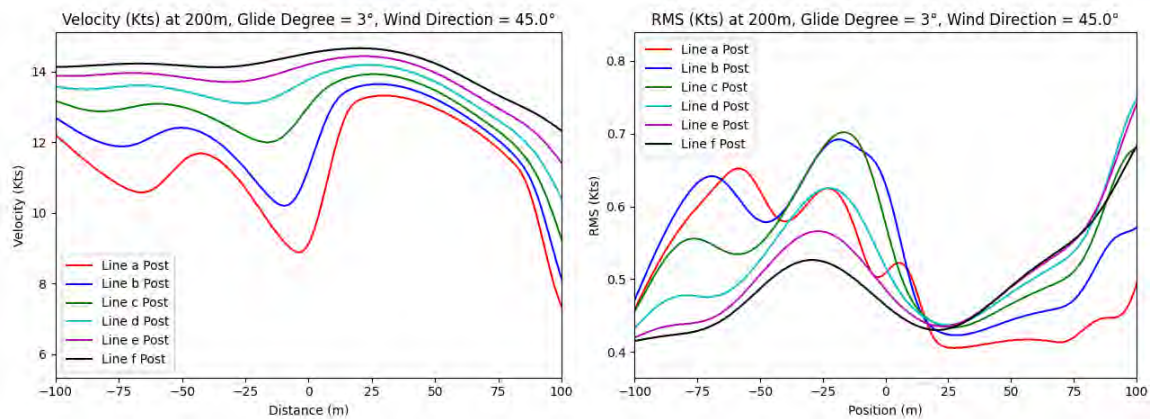


Figure 47: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 45°

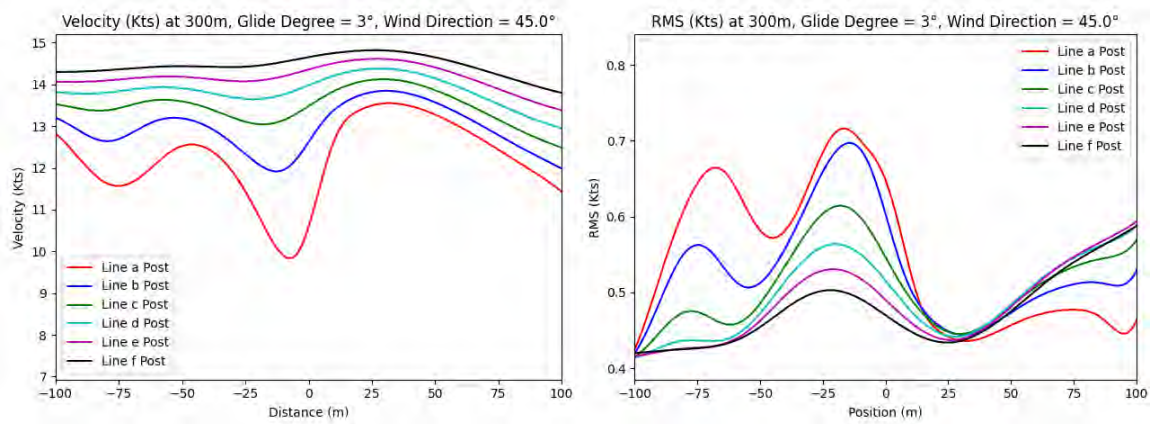


Figure 48: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

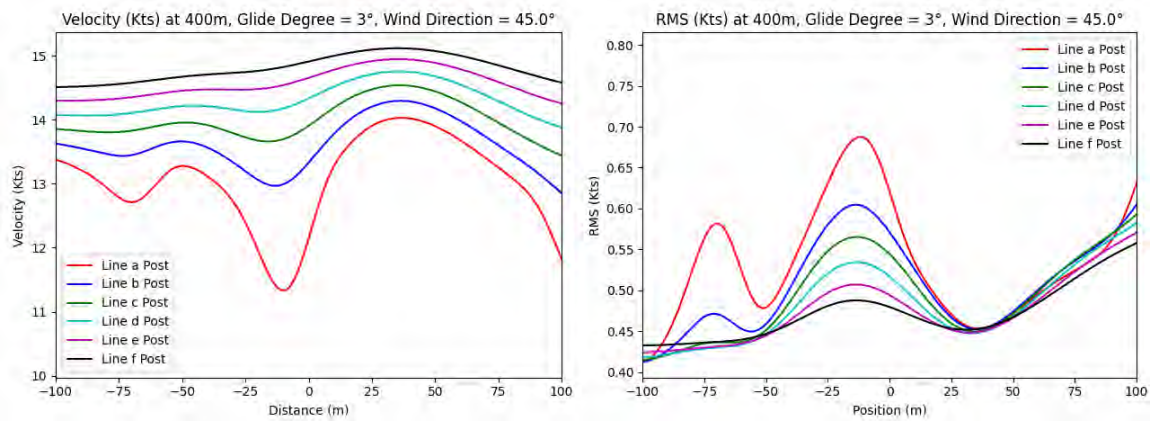


Figure 49: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

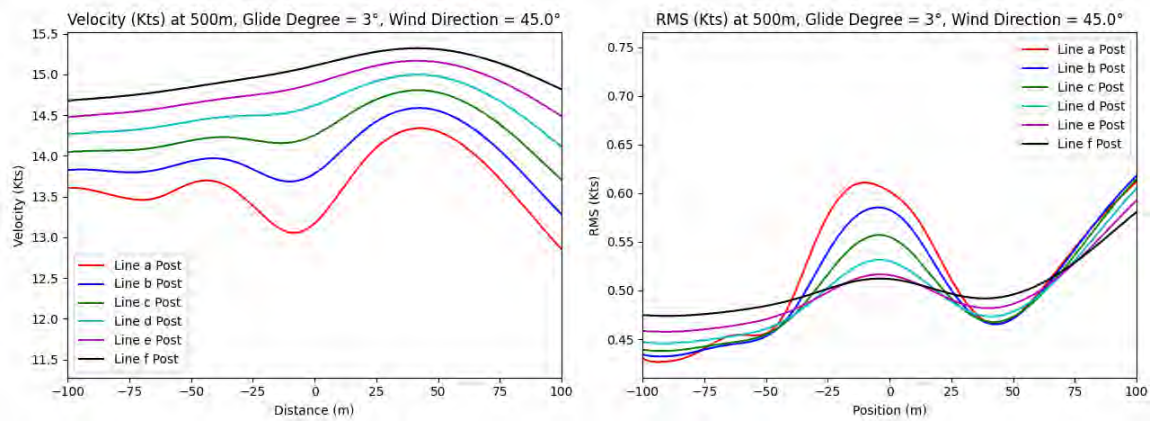


Figure 50: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

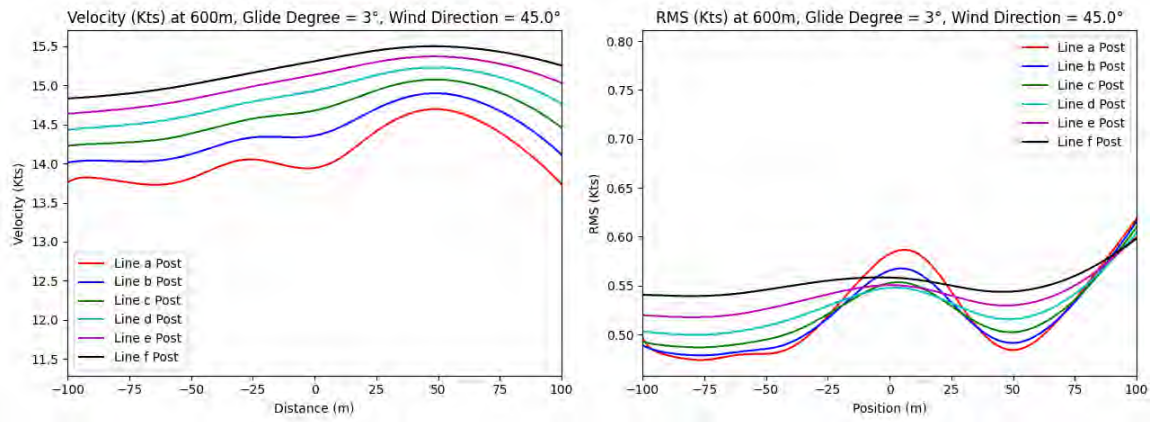


Figure 51: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

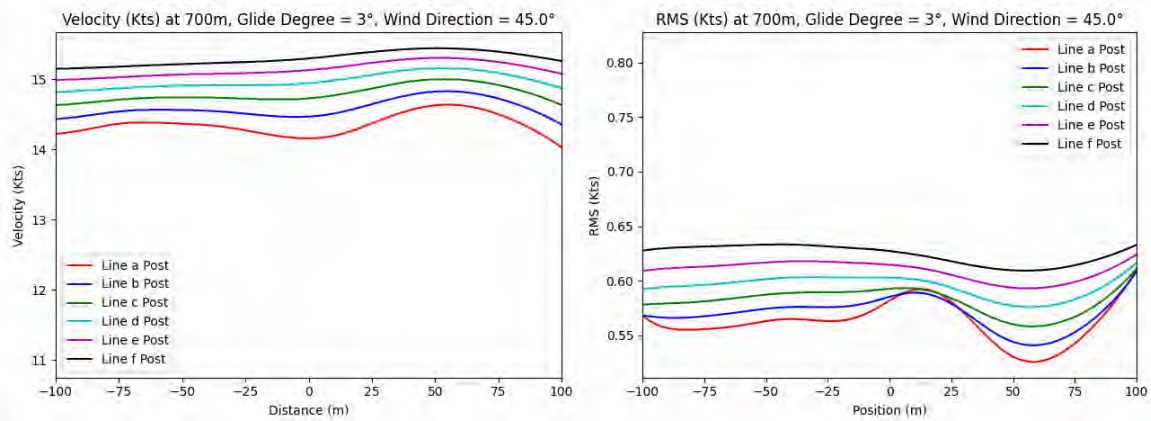


Figure 52: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

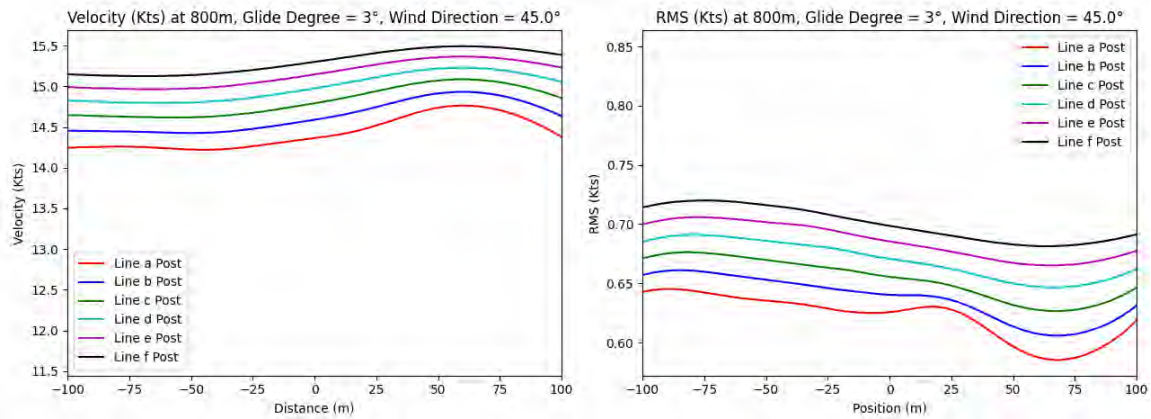


Figure 53: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

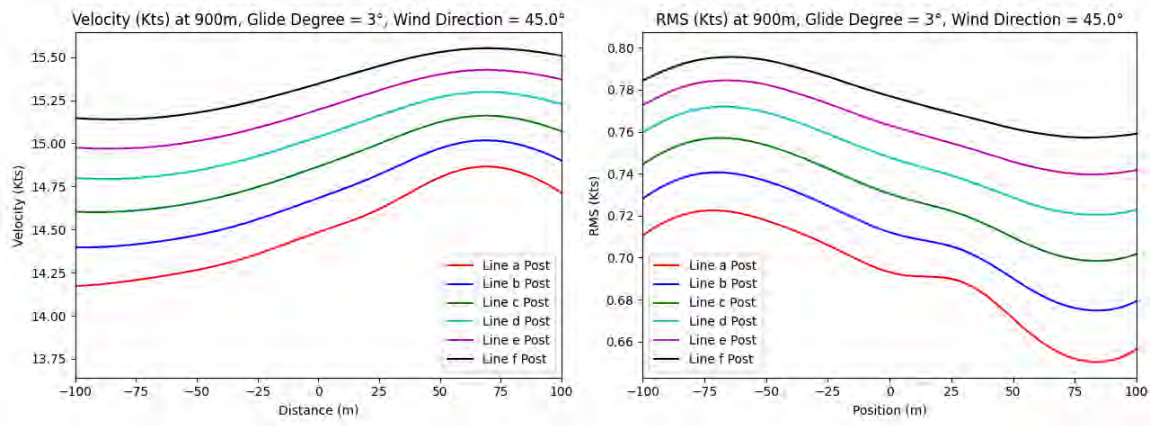


Figure 54: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 45° with 5 m/s approaching speed are shown in tables 3 and 4.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	15.26	15.32	15.34	15.34	15.36	15.38	15.42	15.42	15.35	15.38	15.38	15.39	15.21	15.06	14.95
55	15.08	15.14	15.17	15.17	15.19	15.22	15.26	15.26	15.18	15.21	15.2	15.23	15.04	14.88	14.78
50	14.9	14.97	14.99	15	15.02	15.05	15.09	15.09	15	15.03	15.01	15.05	14.85	14.7	14.59
45	14.71	14.78	14.81	14.81	14.83	14.86	14.91	14.9	14.8	14.81	14.79	14.83	14.63	14.5	14.4
40	14.5	14.58	14.6	14.6	14.62	14.65	14.7	14.69	14.55	14.55	14.5	14.57	14.36	14.28	14.19
35	14.29	14.36	14.38	14.37	14.38	14.42	14.46	14.43	14.25	14.2	14.11	14.24	14.05	14.03	13.95
30	14.06	14.12	14.13	14.11	14.11	14.13	14.16	14.1	13.85	13.76	13.63	13.82	13.67	13.74	13.7
25	13.82	13.86	13.84	13.79	13.76	13.74	13.74	13.64	13.33	13.15	13	13.34	13.22	13.42	13.41
20	13.55	13.56	13.48	13.35	13.2	13.06	12.97	12.79	12.36	11.7	11.83	12.85	12.71	13.05	13.1
15	13.22	13.15	12.95	12.56	12.03	11.54	11.2	10.78	10.07	8.53	8.79	11.88	12.14	12.65	12.74
10	12.73	12.5	11.97	11.04	10.14	9.58	9.27	8.93	8.34	6.99	6.59	8.63	11.54	12.22	12.34
5	11.89	11.38	10.41	9.38	8.94	8.83	8.83	8.76	8.48	7.46	6.95	6.68	10.85	11.67	11.81

Table 3: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 45°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	0.40136	0.39196	0.3868	0.38591	0.3888	0.39557	0.40658	0.42455	0.44714	0.4762	0.51821	0.5634	0.62043	0.67851	0.73959
55	0.41381	0.40252	0.3954	0.39261	0.3937	0.39906	0.4089	0.42577	0.44715	0.47331	0.51271	0.55396	0.60852	0.66334	0.72158
50	0.42354	0.41166	0.40369	0.39991	0.39993	0.40457	0.41399	0.43051	0.45146	0.4755	0.51256	0.54847	0.59793	0.6487	0.70372
45	0.43056	0.41935	0.41169	0.40796	0.40786	0.41261	0.4225	0.43963	0.46123	0.48467	0.52029	0.54866	0.58915	0.6342	0.68531
40	0.43397	0.42468	0.41861	0.41615	0.4172	0.42309	0.43443	0.45328	0.47713	0.50197	0.53815	0.55613	0.58326	0.62039	0.6667
35	0.43337	0.42714	0.42389	0.42397	0.42752	0.4358	0.44958	0.47117	0.49888	0.52633	0.56417	0.57026	0.58111	0.60782	0.64827
30	0.42911	0.42694	0.42779	0.43207	0.44006	0.45238	0.46963	0.49374	0.52418	0.55237	0.58907	0.58587	0.58218	0.59676	0.63031
25	0.42233	0.42541	0.43225	0.44396	0.46098	0.48084	0.50322	0.52744	0.55671	0.57934	0.60464	0.59353	0.58338	0.58649	0.61264
20	0.41523	0.42555	0.44232	0.4688	0.50434	0.53935	0.57068	0.59557	0.62279	0.64169	0.63735	0.58558	0.57873	0.5747	0.59398
15	0.41118	0.43228	0.46587	0.51583	0.5673	0.60095	0.62171	0.63604	0.64509	0.66551	0.67588	0.58293	0.56082	0.55635	0.57111
10	0.41319	0.44649	0.49153	0.52479	0.51287	0.48861	0.47513	0.47561	0.48791	0.54452	0.62151	0.60317	0.52221	0.5233	0.53826
5	0.4168	0.4425	0.44401	0.38962	0.32784	0.3167	0.33703	0.37393	0.43759	0.54232	0.65953	0.57643	0.44812	0.4652	0.4851

Table 4: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 45°

Wind Direction = 60°

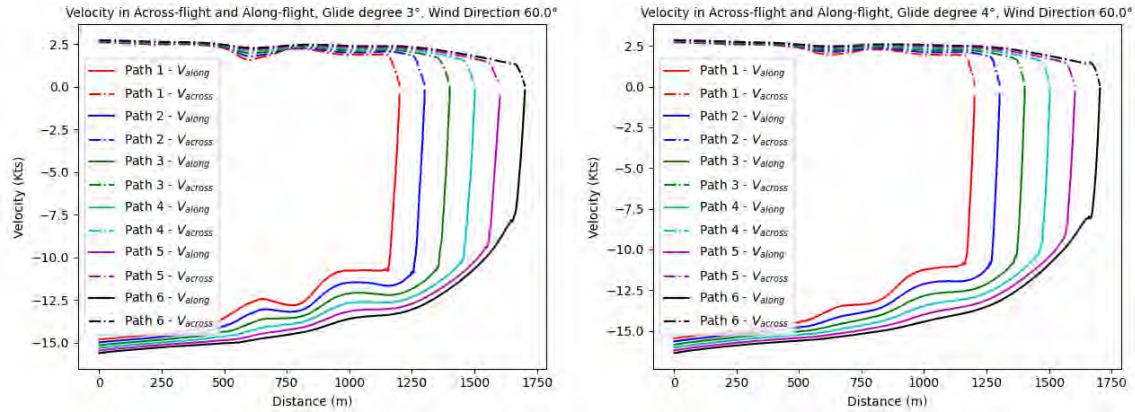


Figure 55: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 5 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 60°

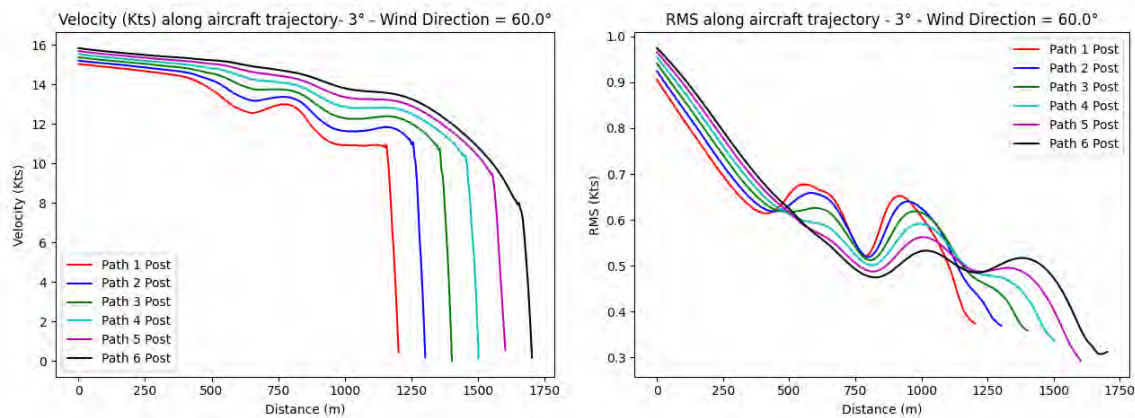


Figure 56: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 5(m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

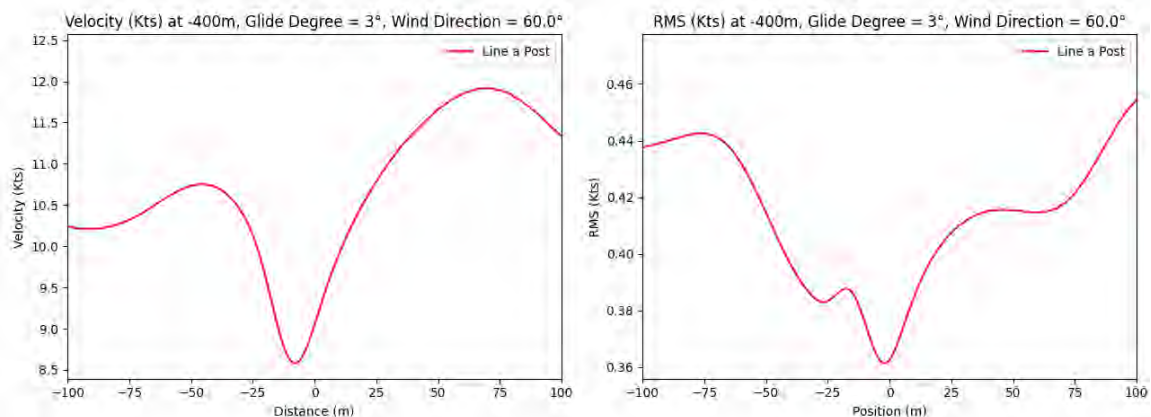


Figure 57: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

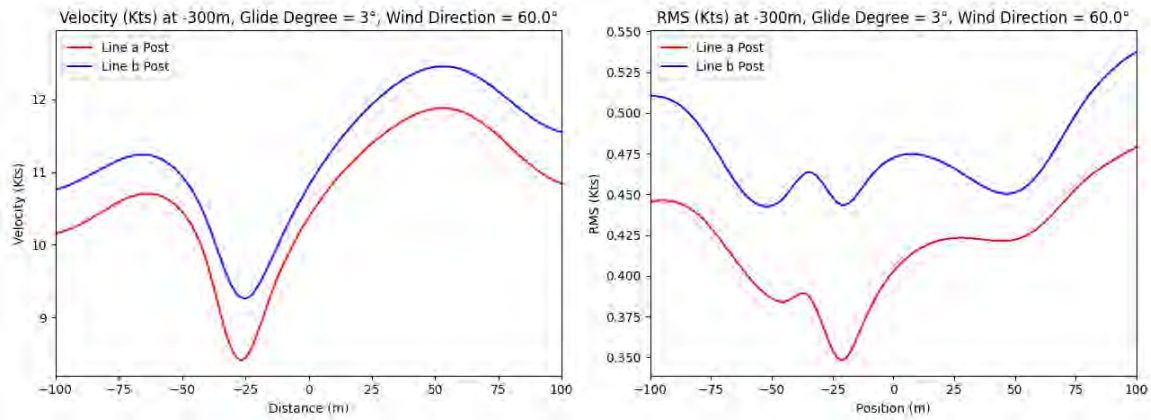


Figure 58: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

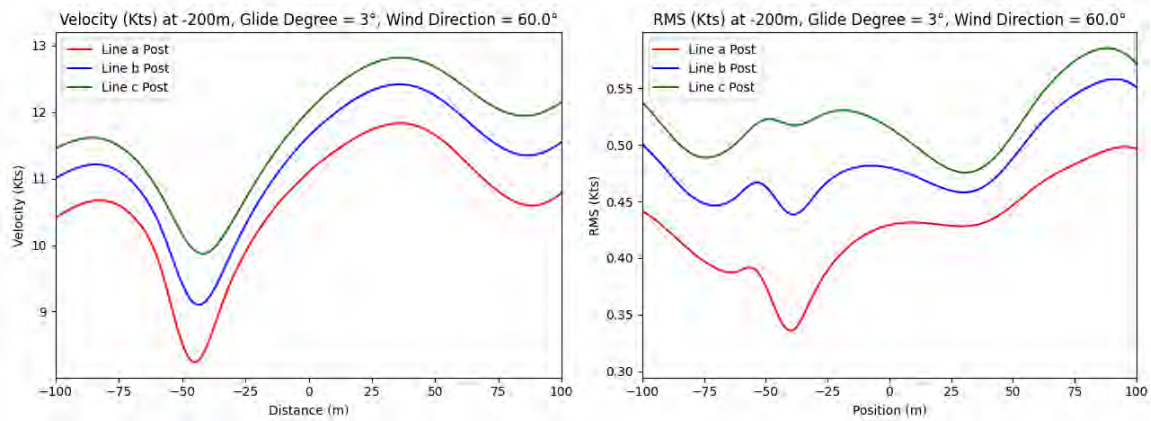


Figure 59: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

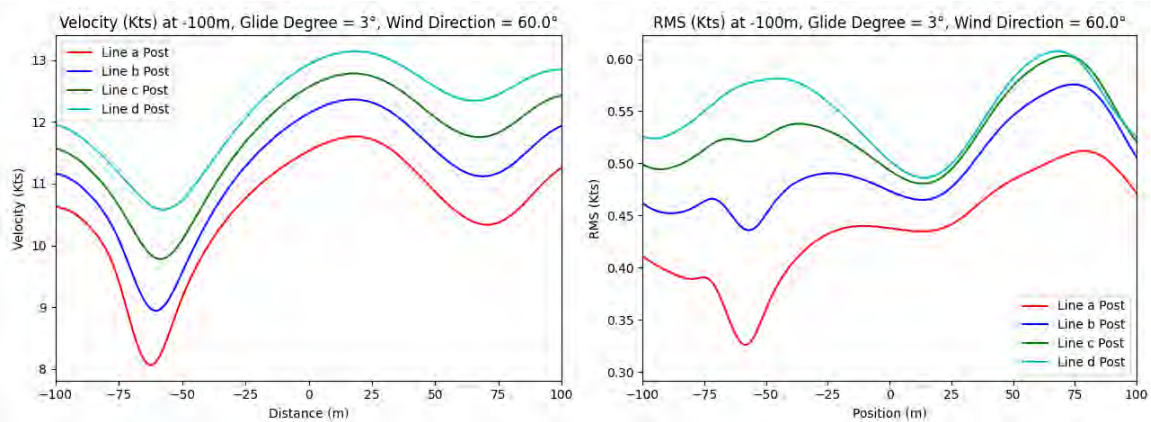


Figure 60: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

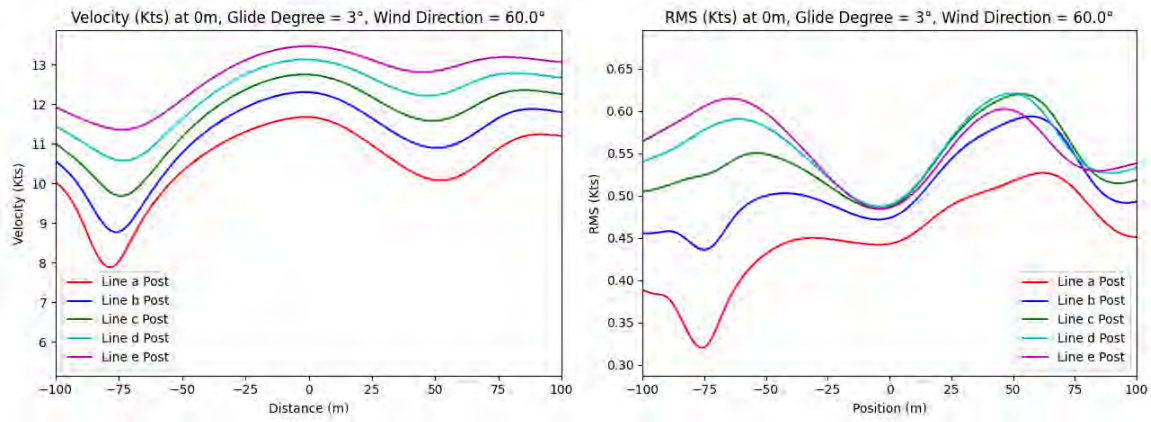


Figure 61: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

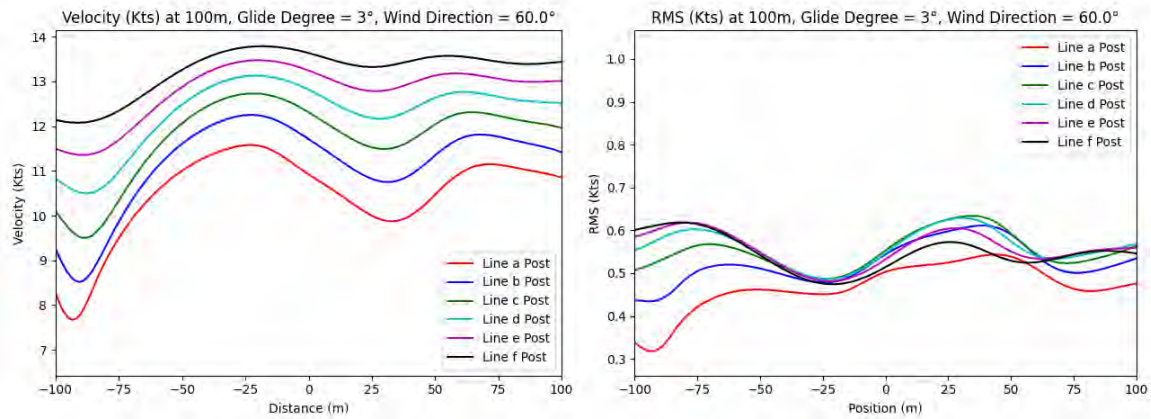


Figure 62: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

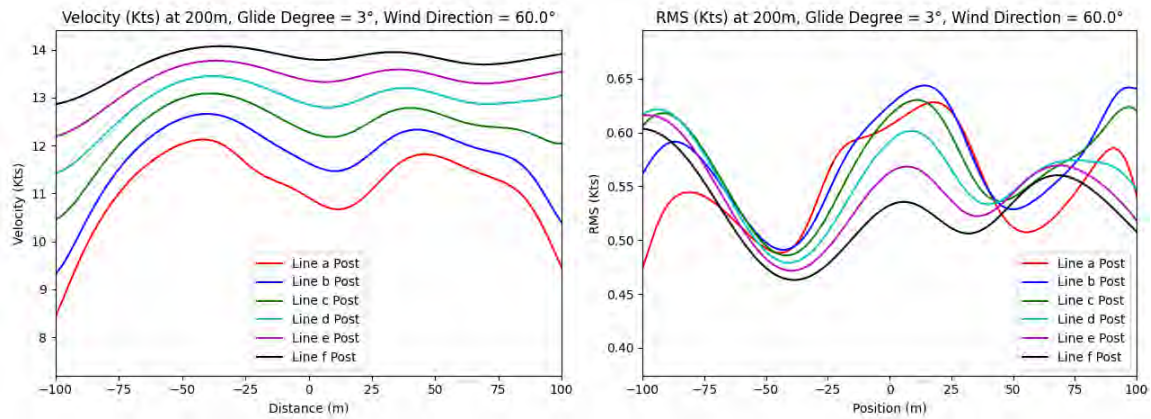


Figure 63: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

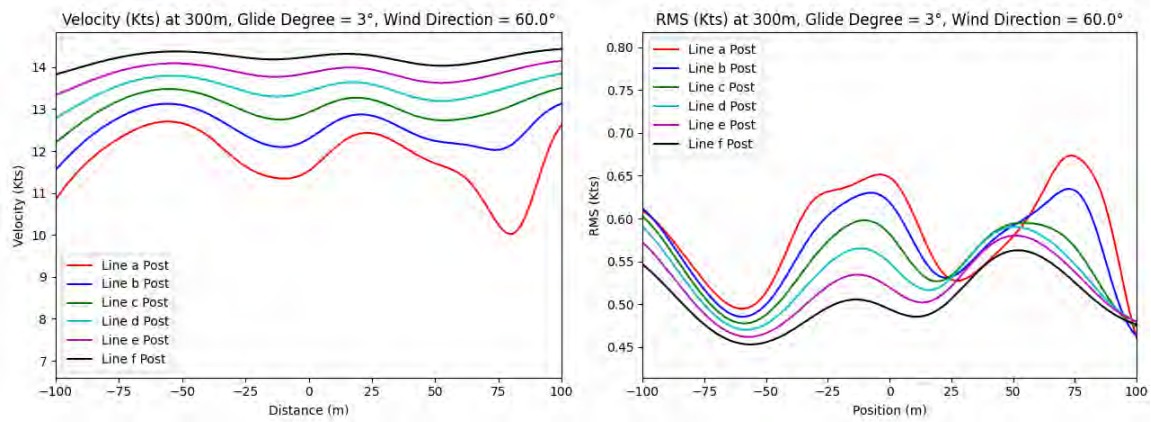


Figure 64: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

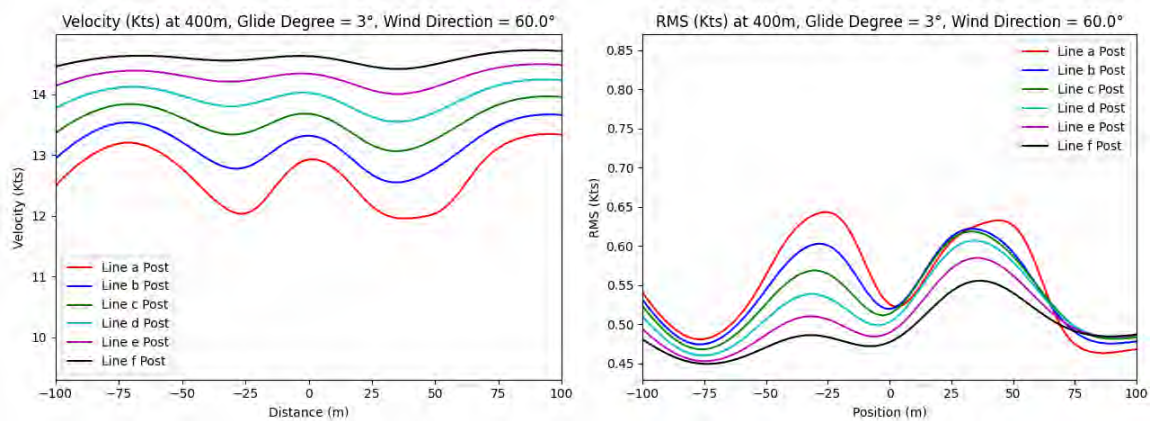


Figure 65: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

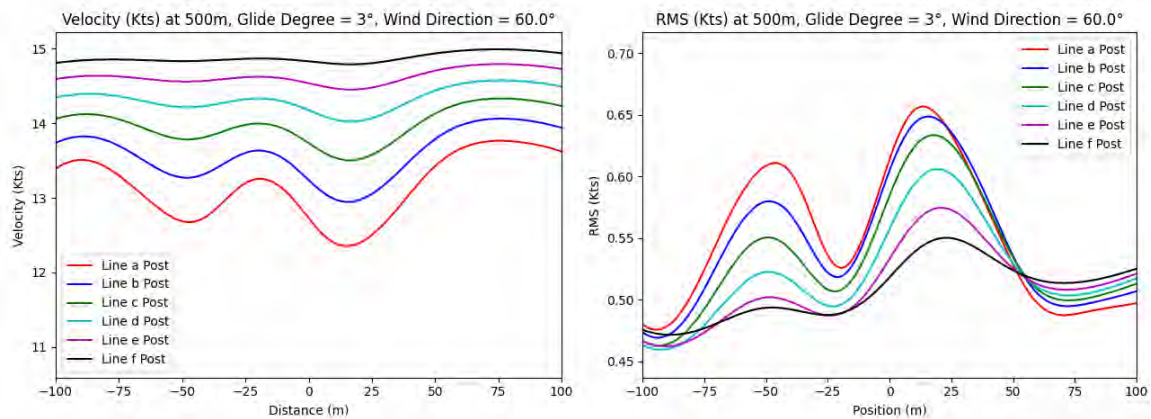


Figure 66: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

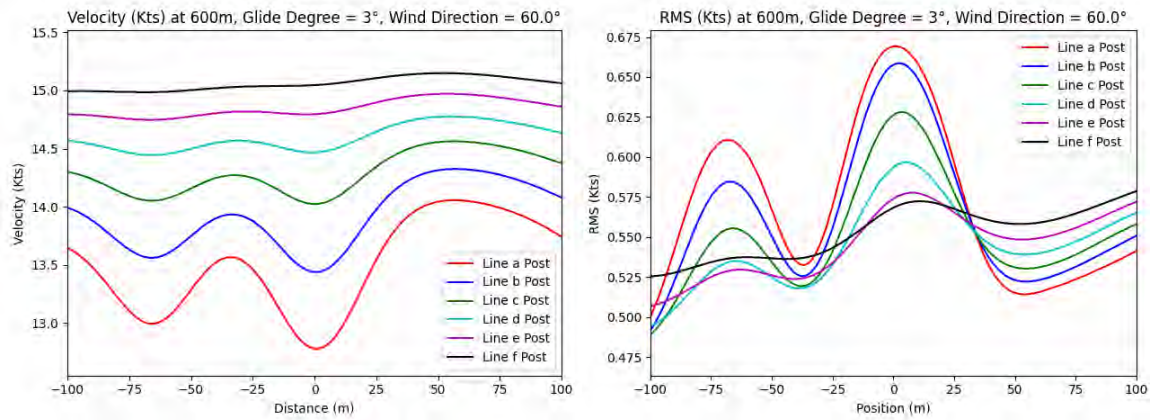


Figure 67: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

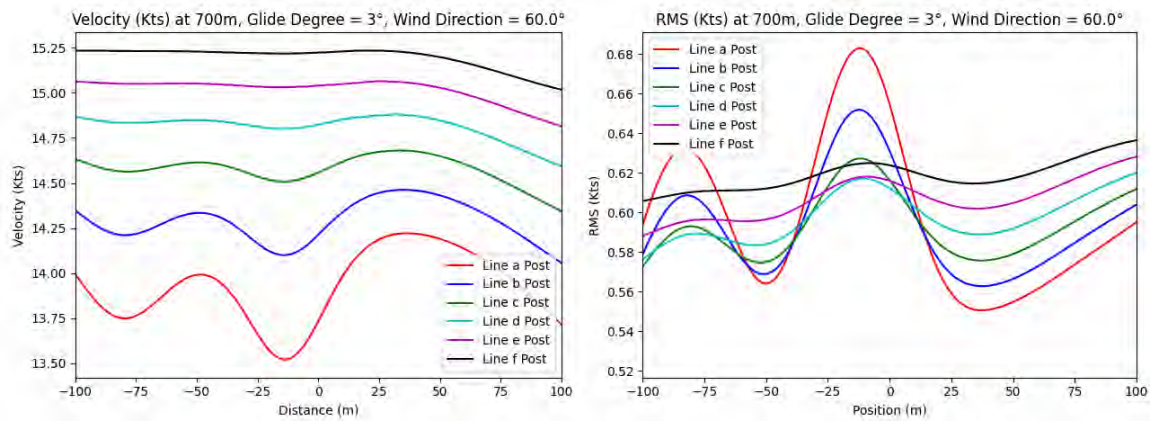


Figure 68: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

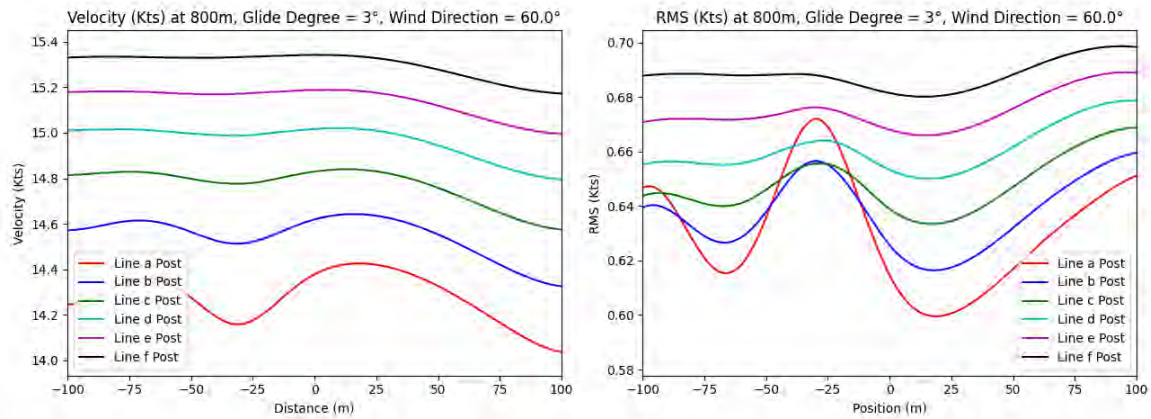


Figure 69: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction = 60°

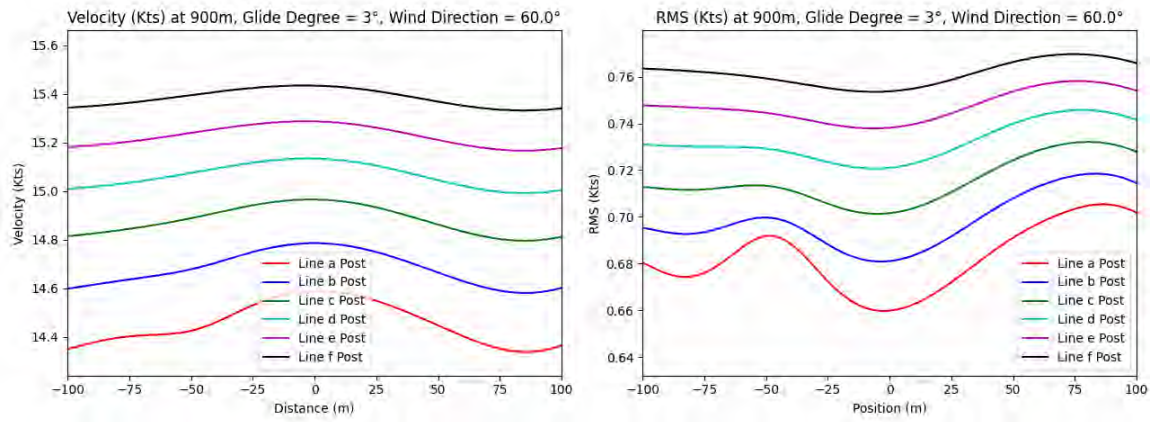


Figure 70: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 5 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 60° with 5 m/s approaching speed are shown in tables 5 and 6.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	14.45	14.49	14.65	14.85	15.02	15.11	15.15	15.17	15.2	15.19	15.18	15.15	15.13	15.11	15.05
55	14.09	14.1	14.3	14.59	14.81	14.92	14.95	14.95	14.98	14.99	14.96	14.93	14.94	14.93	14.88
50	13.72	13.69	13.93	14.3	14.59	14.72	14.74	14.71	14.74	14.77	14.71	14.66	14.71	14.74	14.7
45	13.32	13.24	13.53	13.98	14.34	14.5	14.49	14.41	14.45	14.51	14.41	14.31	14.43	14.53	14.5
40	12.89	12.75	13.1	13.64	14.07	14.25	14.2	14.06	14.11	14.23	14.03	13.83	14.05	14.28	14.29
35	12.45	12.24	12.67	13.3	13.78	13.98	13.88	13.67	13.73	13.92	13.59	13.24	13.55	14	14.04
30	12	11.71	12.25	12.97	13.49	13.7	13.53	13.23	13.3	13.58	13.11	12.6	12.96	13.66	13.77
25	11.55	11.18	11.84	12.63	13.19	13.39	13.16	12.74	12.78	13.23	12.63	11.91	12.36	13.3	13.47
20	11.11	10.65	11.45	12.29	12.86	13.06	12.73	12.18	12.15	12.84	12.13	10.68	11.8	12.93	13.12
15	10.66	10.12	11.1	11.95	12.51	12.69	12.24	11.55	11.4	12.37	11.63	8.24	11.28	12.58	12.73
10	10.19	9.6	10.76	11.58	12.09	12.26	11.66	10.86	10.55	11.69	11.2	6.11	10.82	12.22	12.27
5	9.61	9.03	10.34	11.06	11.49	11.64	10.88	10.05	9.54	10.58	10.68	6.74	10.39	11.78	11.63

Table 5: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 60°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	0.5045	0.50989	0.49041	0.45664	0.42933	0.41988	0.42666	0.44065	0.45182	0.47211	0.51654	0.56942	0.61939	0.66097	0.71171
55	0.53709	0.54849	0.52559	0.48119	0.44234	0.42774	0.43511	0.4495	0.45523	0.46898	0.51483	0.56932	0.61354	0.64628	0.69157
50	0.5632	0.58171	0.55788	0.50572	0.45665	0.437	0.44664	0.46401	0.46469	0.47205	0.52281	0.58071	0.61329	0.63301	0.67161
45	0.58267	0.60768	0.58467	0.52861	0.47201	0.44806	0.46197	0.48565	0.48121	0.48116	0.54115	0.60541	0.62148	0.62124	0.65122
40	0.59343	0.62318	0.60221	0.54607	0.48621	0.45993	0.48036	0.51259	0.50333	0.49371	0.5662	0.63851	0.64005	0.61201	0.63102
35	0.59443	0.62631	0.60877	0.55594	0.49714	0.47104	0.49981	0.5414	0.5288	0.5059	0.59073	0.66375	0.66342	0.60572	0.61179
30	0.58546	0.61618	0.6039	0.55777	0.50369	0.48015	0.51848	0.57013	0.55763	0.51486	0.60706	0.66816	0.67554	0.60062	0.59418
25	0.56691	0.59281	0.58744	0.55142	0.50569	0.48656	0.53499	0.59731	0.59122	0.52045	0.61275	0.6576	0.66694	0.59253	0.57834
20	0.5393	0.55654	0.55925	0.53627	0.5024	0.48911	0.54753	0.61837	0.62678	0.52755	0.61018	0.69334	0.63926	0.57711	0.56349
15	0.50241	0.50704	0.51932	0.51156	0.49205	0.48536	0.5522	0.62424	0.6509	0.54757	0.59681	0.72572	0.59435	0.54922	0.54684
10	0.45364	0.44265	0.46673	0.47603	0.47175	0.47139	0.54131	0.60266	0.64407	0.58835	0.566	0.59591	0.53047	0.50567	0.52217
5	0.38392	0.35737	0.39872	0.42628	0.43598	0.4408	0.49984	0.53398	0.5793	0.6055	0.54016	0.61572	0.43336	0.44094	0.47577

Table 6: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 60°

Reference Wind Speed at 10m above ground = 10m/s
Wind Direction = 30°

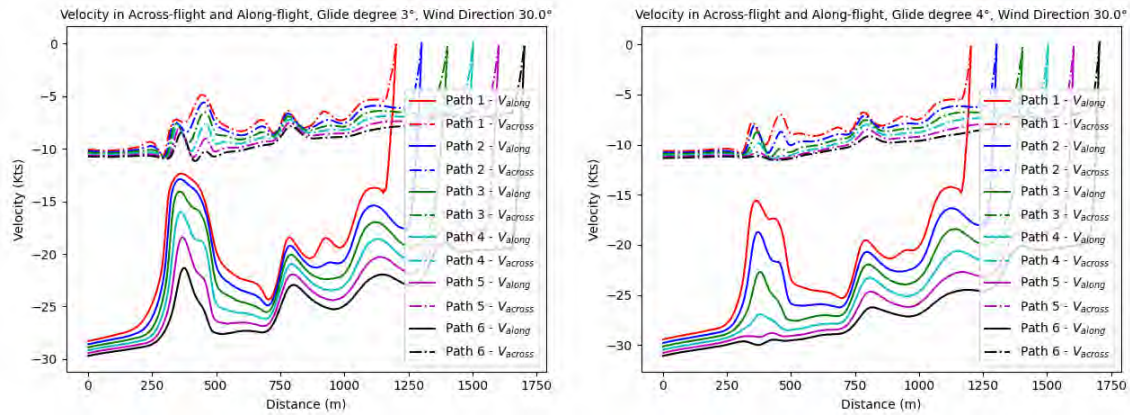


Figure 71: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 10 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 30°

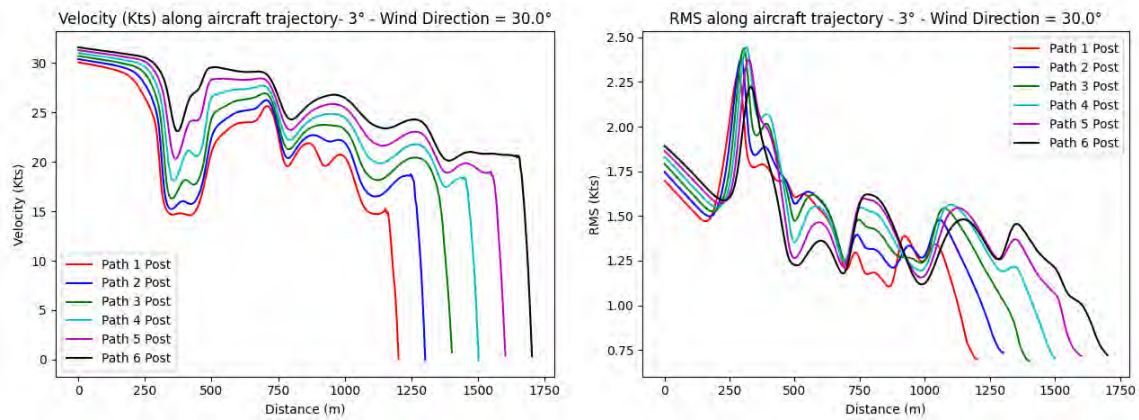


Figure 72: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 10(m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

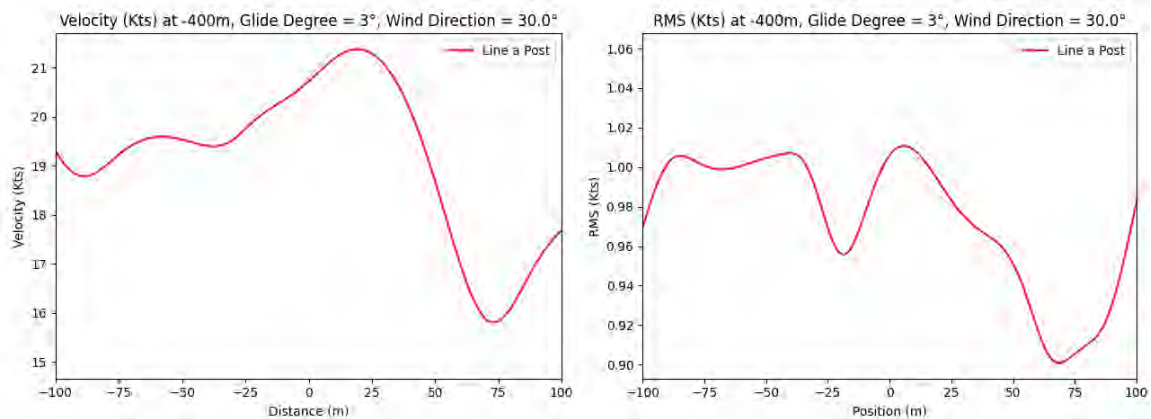


Figure 73: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

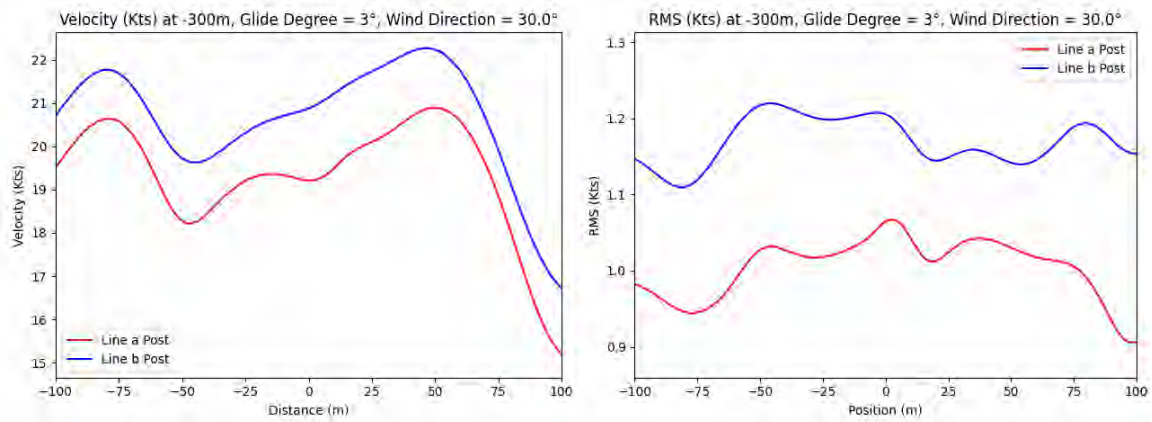


Figure 74: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

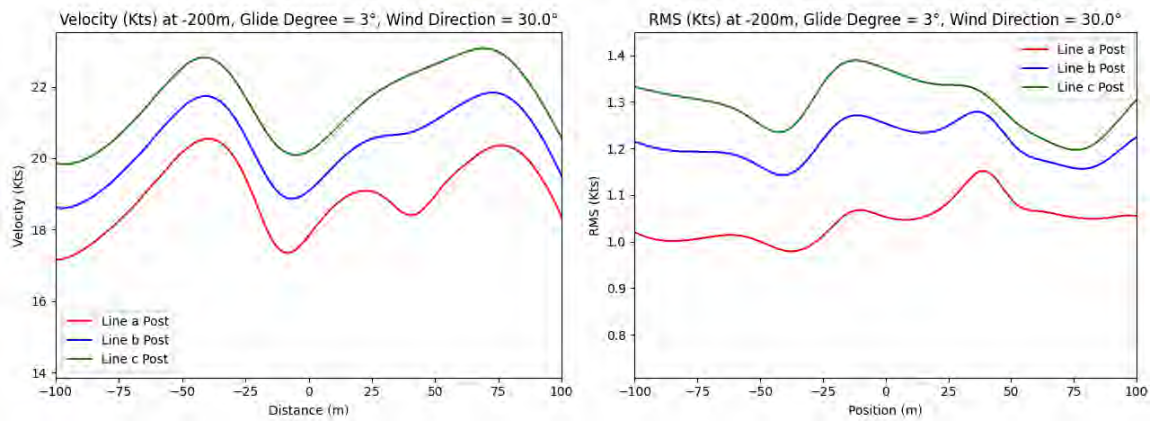


Figure 75: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

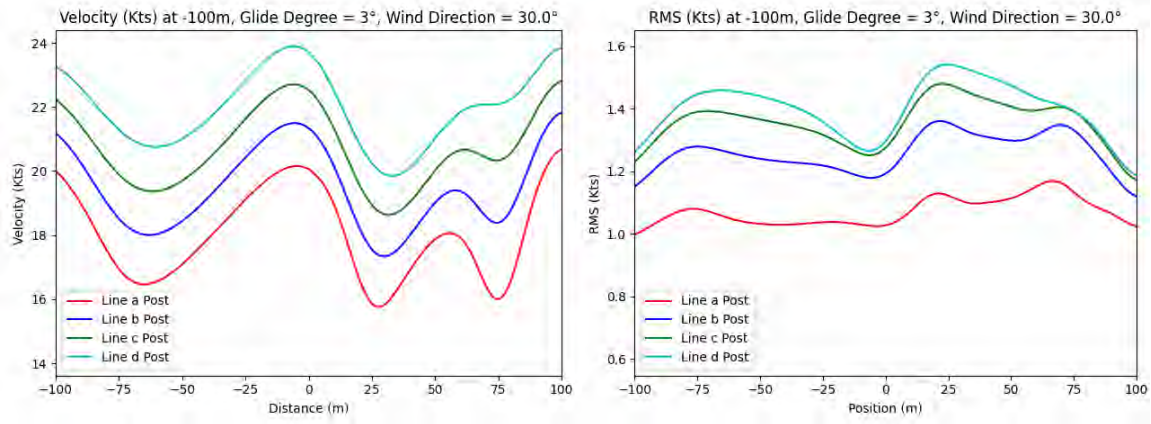


Figure 76: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

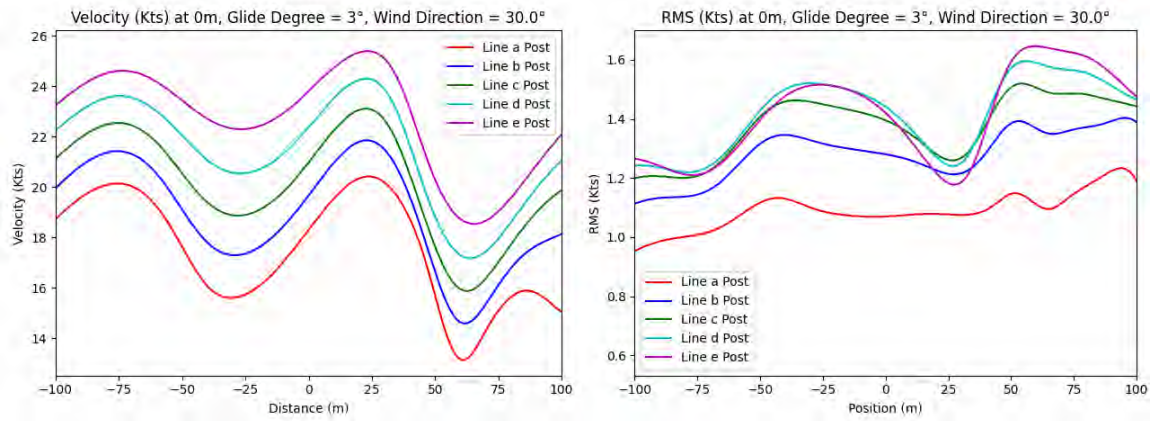


Figure 77: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

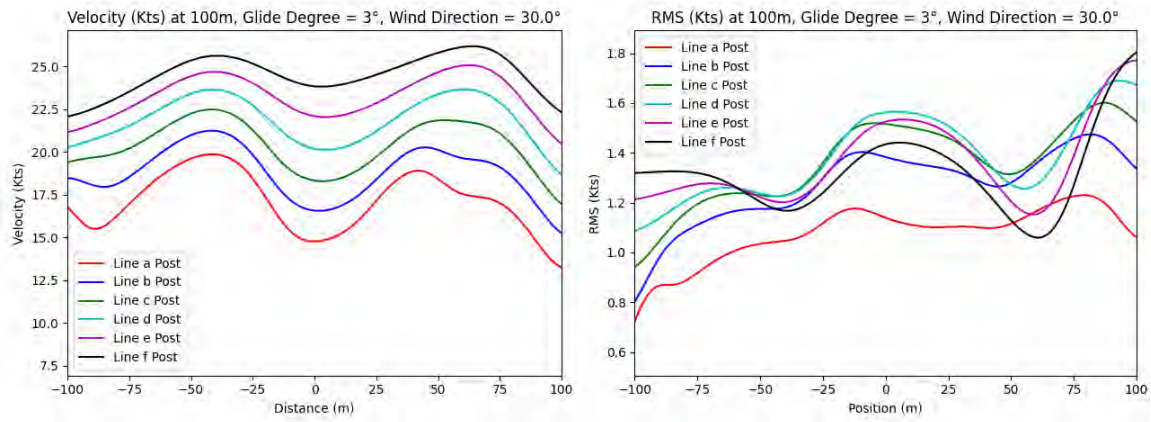


Figure 78: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

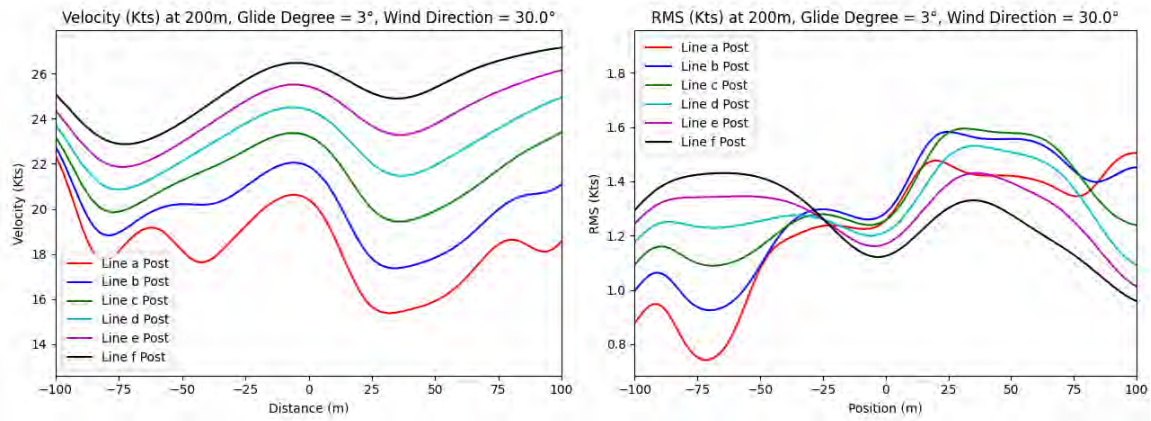


Figure 79: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

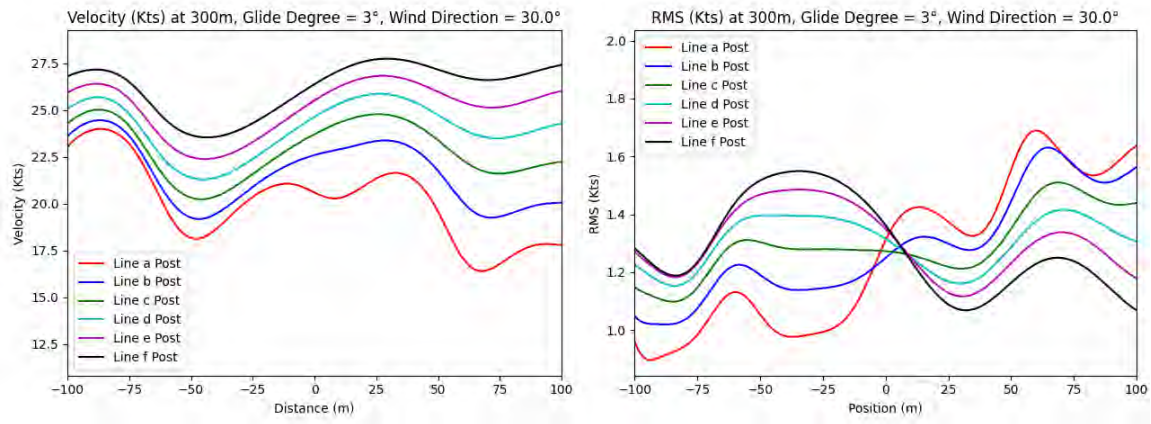


Figure 80: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

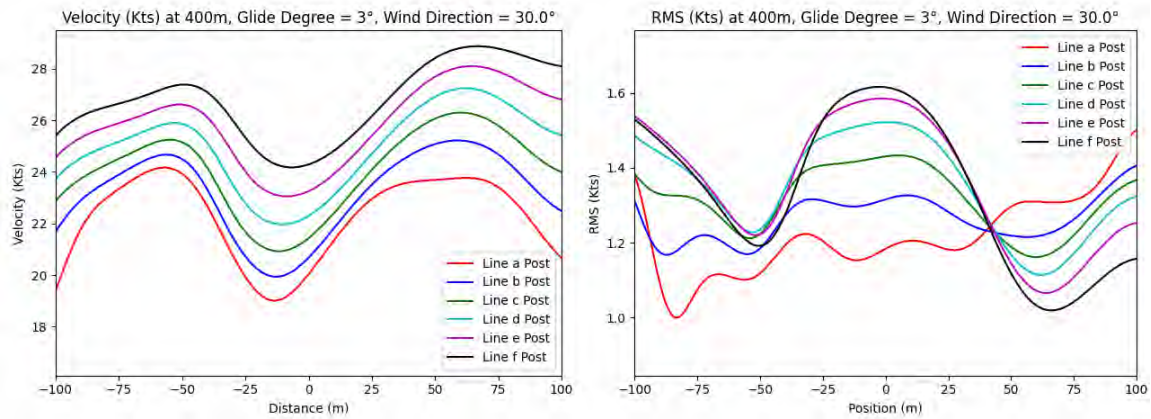


Figure 81: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

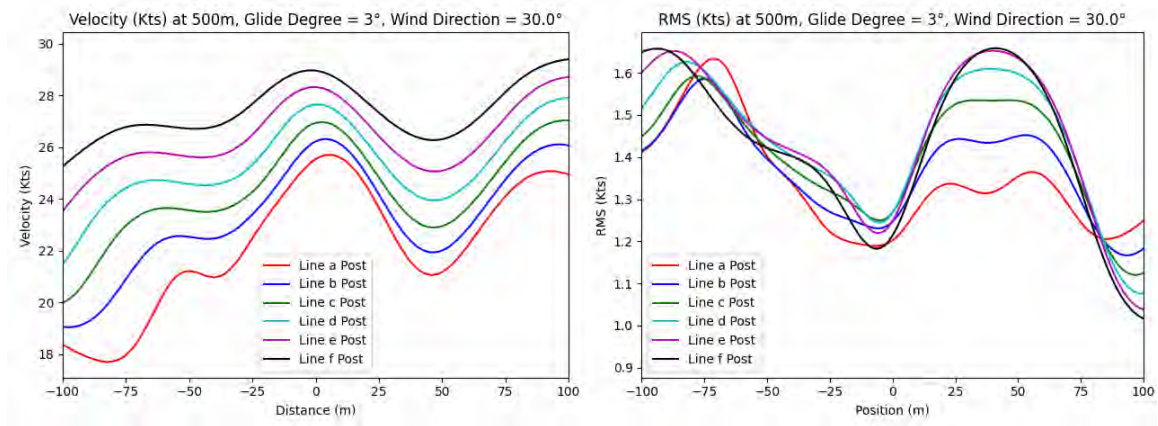


Figure 82: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

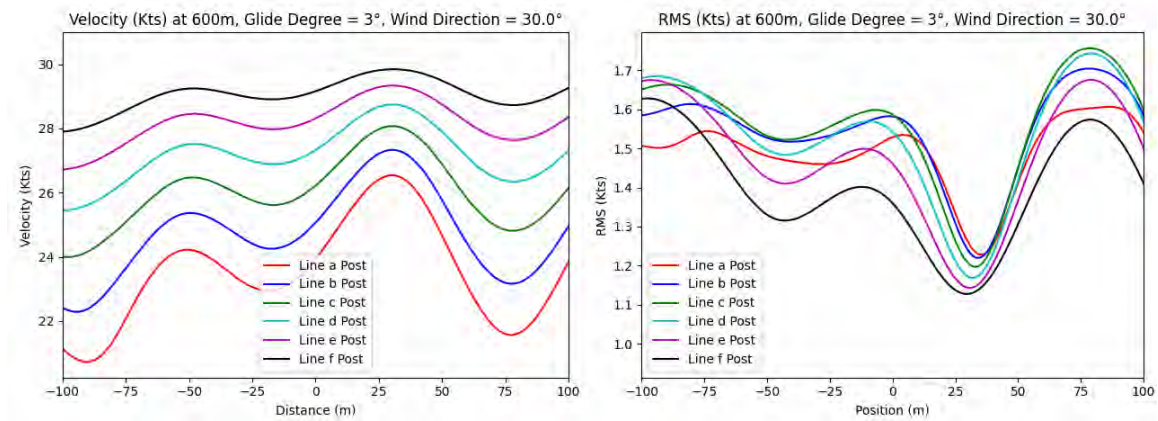


Figure 83: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

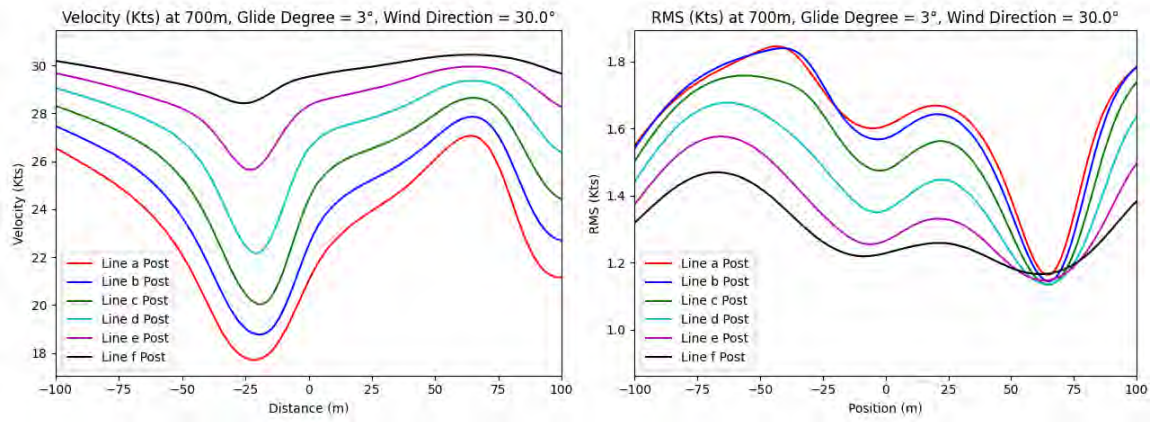


Figure 84: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

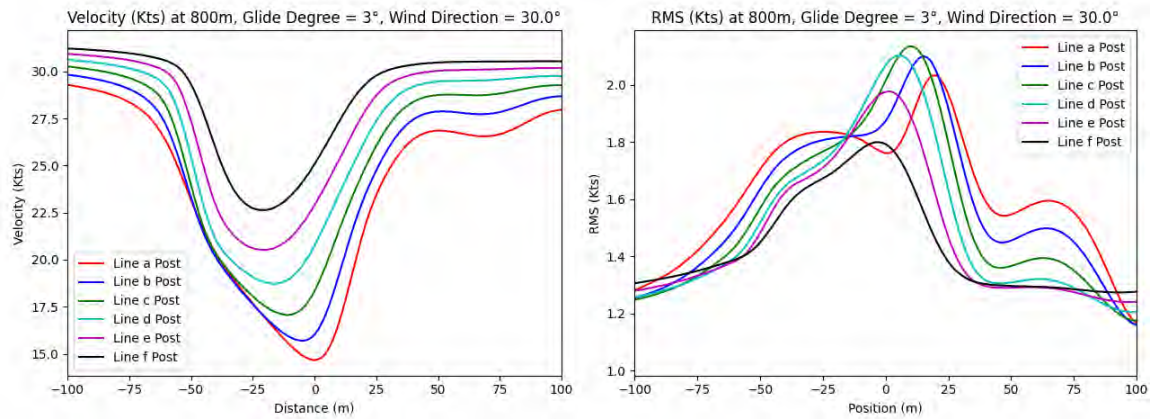


Figure 85: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

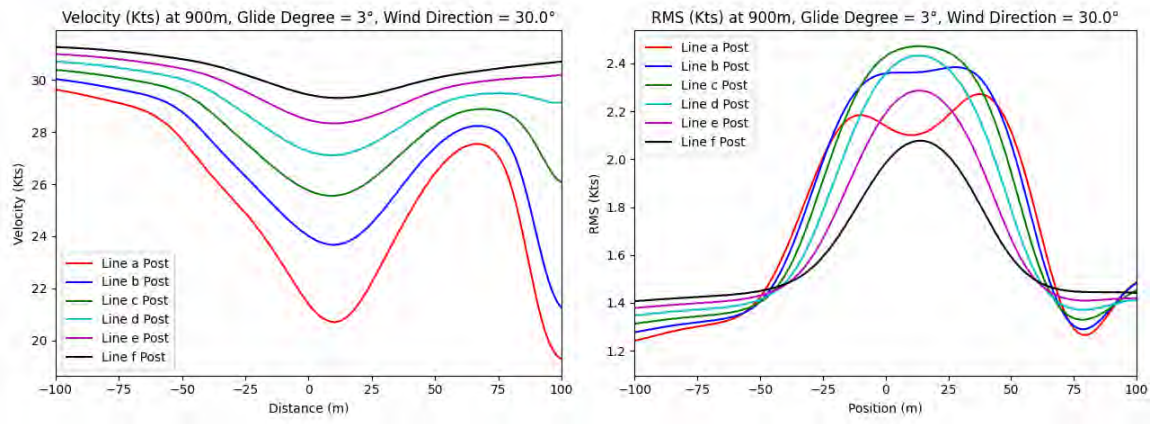


Figure 86: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 30° with 10 m/s approaching speed are shown in tables 7 and 8.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	29.36	29.91	29.65	29.4	30	30.03	29.81	29.92	29.27	27.25	29.83	29.54	28.85	21.81	26.58
55	28.62	29.41	28.99	28.53	29.47	29.48	29.11	29.36	28.49	25.94	29.26	28.75	27.46	19.49	24.95
50	27.87	28.89	28.32	27.59	28.9	28.84	28.3	28.71	27.71	24.88	28.68	27.87	25.57	17.08	23.05
45	27.1	28.31	27.58	26.52	28.23	28.05	27.33	27.94	26.89	23.86	28.05	26.88	23.6	15.35	20.02
40	26.34	27.65	26.79	25.42	27.47	27.11	26.2	27.06	26.06	22.89	27.39	25.8	21.92	14.46	17.5
35	25.61	26.94	25.94	24.34	26.6	26.02	24.9	26.13	25.22	22	26.7	24.69	20.62	14.13	16.54
30	24.89	26.15	25.04	23.26	25.64	24.79	23.4	25.17	24.38	21.2	26.01	23.61	19.63	14.12	16.24
25	24.2	25.27	24.08	22.17	24.61	23.46	21.67	24.16	23.48	20.5	25.37	22.61	18.78	14.26	16.38
20	23.52	24.31	23.07	21.1	23.51	22.09	19.84	23.01	22.34	19.91	24.8	21.72	18.02	14.45	16.84
15	22.85	23.25	21.98	20.03	22.38	20.77	18.08	21.7	20.2	19.44	24.33	20.96	17.36	14.63	17.5
10	22.13	22.09	20.74	18.97	21.24	19.52	16.42	20.29	16.22	19.07	23.91	20.32	16.82	14.73	18.24
5	21.17	20.62	19.12	17.76	19.99	18.2	14.69	18.82	13.47	18.59	23.39	19.71	16.42	14.62	18.91

Table 7: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 30°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	1.00131	0.8568	0.9731	1.03841	0.83247	0.86354	0.93445	0.92533	1.2179	1.52104	1.14799	1.30922	1.24394	2.0371	2.40865
55	1.09054	0.90821	1.06211	1.16356	0.87158	0.90901	0.99929	0.95675	1.28591	1.59373	1.18929	1.4126	1.30244	2.05497	2.41239
50	1.16621	0.96206	1.14475	1.27588	0.92202	0.97101	1.07721	0.99738	1.33396	1.61691	1.22619	1.50338	1.40742	1.94228	2.27728
45	1.22562	1.01953	1.2207	1.37088	0.98651	1.0551	1.16704	1.04535	1.36064	1.60719	1.25419	1.56726	1.518	1.81709	2.03322
40	1.26518	1.07604	1.28335	1.43838	1.06247	1.15882	1.26254	1.0939	1.36297	1.56596	1.26705	1.59166	1.58873	1.73456	1.84329
35	1.28419	1.12745	1.32835	1.47821	1.14369	1.2716	1.36172	1.13831	1.34251	1.49595	1.26057	1.5705	1.60604	1.67239	1.75332
30	1.28298	1.17009	1.35231	1.49219	1.21842	1.37077	1.46083	1.17973	1.30516	1.40144	1.23443	1.50679	1.57413	1.60456	1.70185
25	1.26173	1.19889	1.35299	1.47865	1.27243	1.43277	1.54014	1.22239	1.26388	1.28728	1.18811	1.40887	1.49806	1.51738	1.65332
20	1.21974	1.20694	1.32907	1.43546	1.29202	1.43945	1.56155	1.26303	1.24942	1.1583	1.12359	1.28405	1.38174	1.40613	1.58747
15	1.15498	1.18518	1.27896	1.35918	1.26464	1.38498	1.50389	1.28249	1.3229	1.01758	1.04162	1.13196	1.22357	1.26764	1.49213
10	1.06243	1.12336	1.19705	1.24039	1.17947	1.26674	1.36723	1.24544	1.29633	0.86099	0.93928	0.94486	1.01654	1.09485	1.35133
5	0.92573	0.99723	1.05359	1.04021	1.01621	1.05643	1.1234	1.10209	0.9315	0.67876	0.80982	0.69661	0.74117	0.85366	1.11218

Table 8: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 30°

Wind Direction = 45°

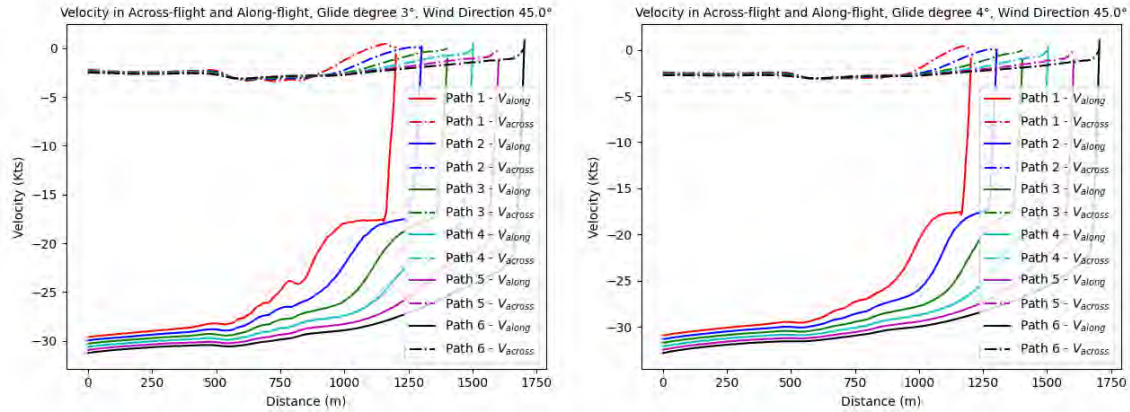


Figure 87: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 10 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 45°

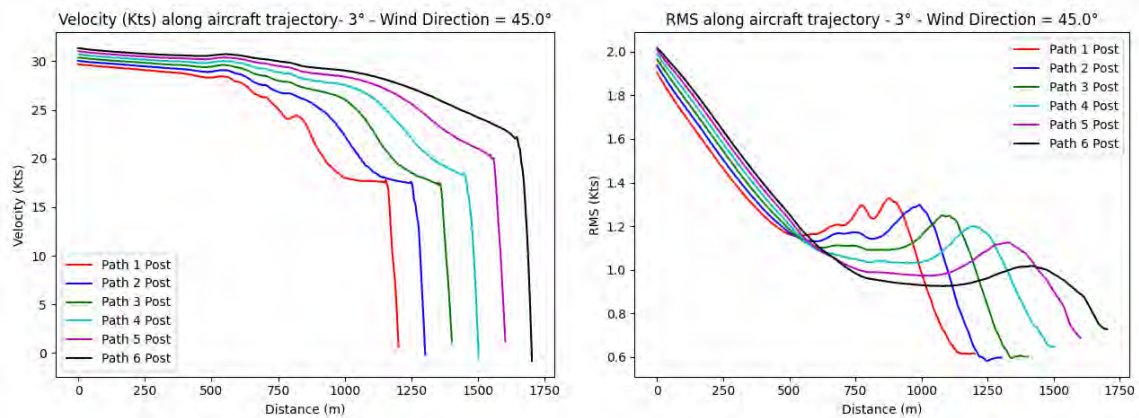


Figure 88: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 10(m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

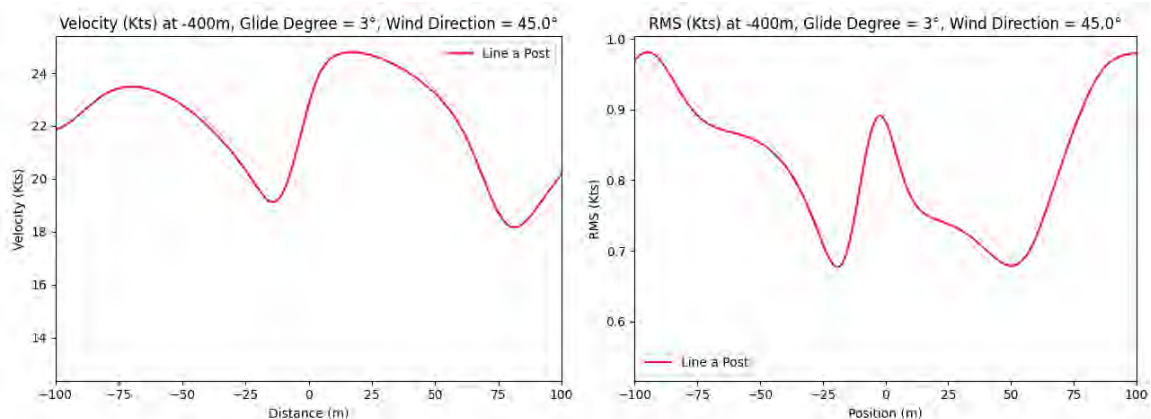


Figure 89: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

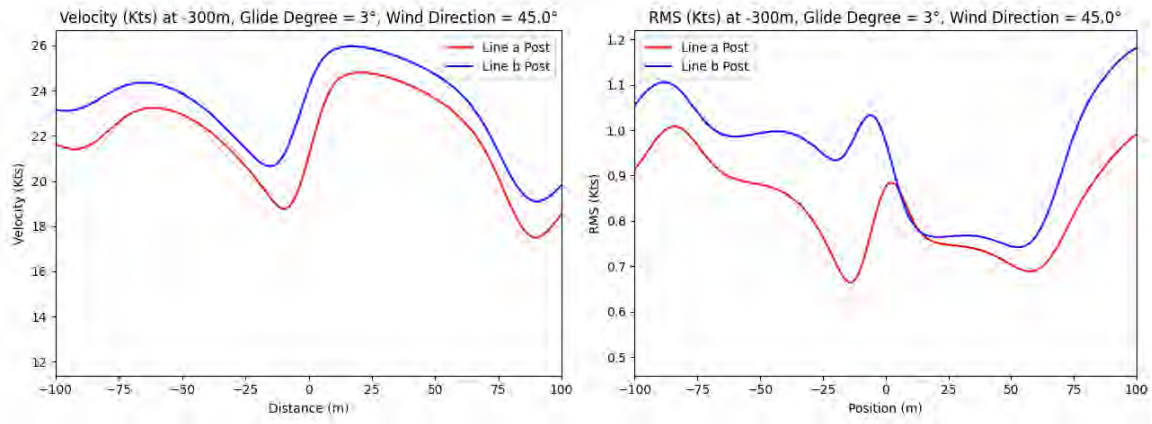


Figure 90: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

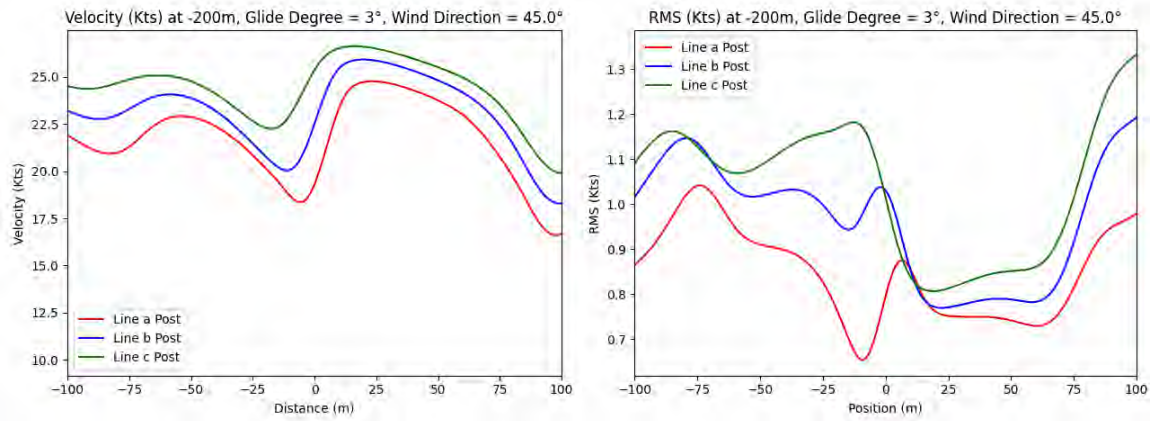


Figure 91: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

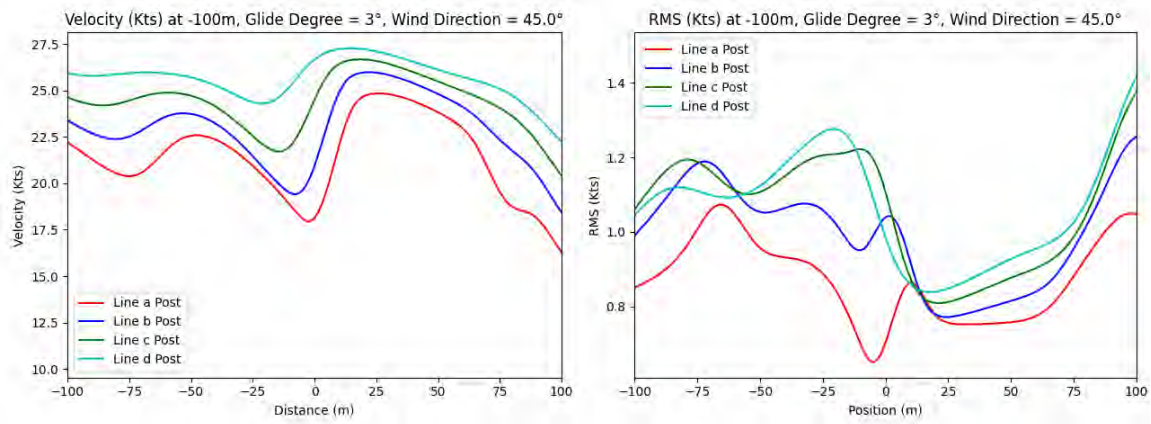


Figure 92: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

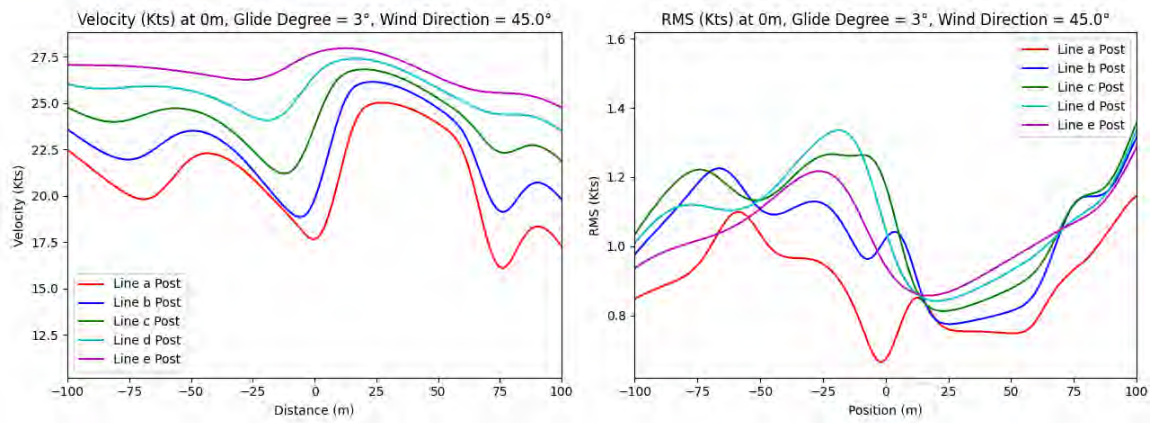


Figure 93: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

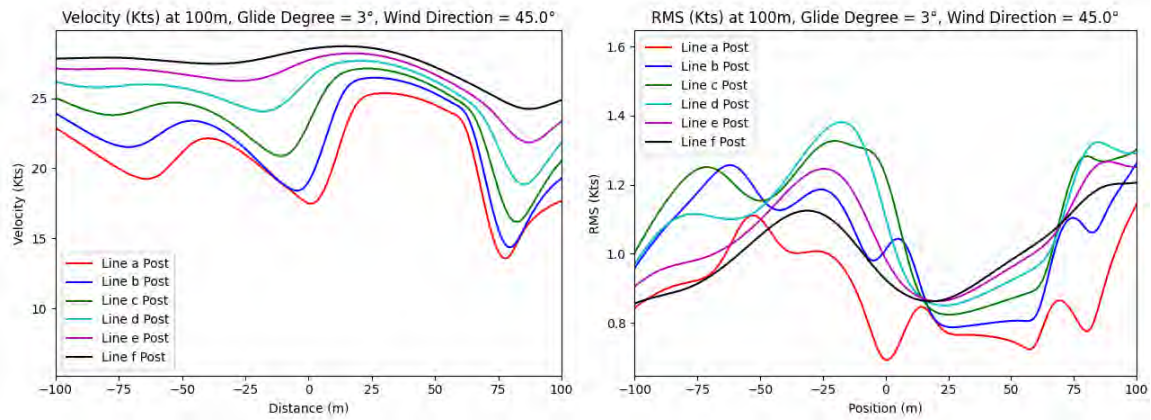


Figure 94: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

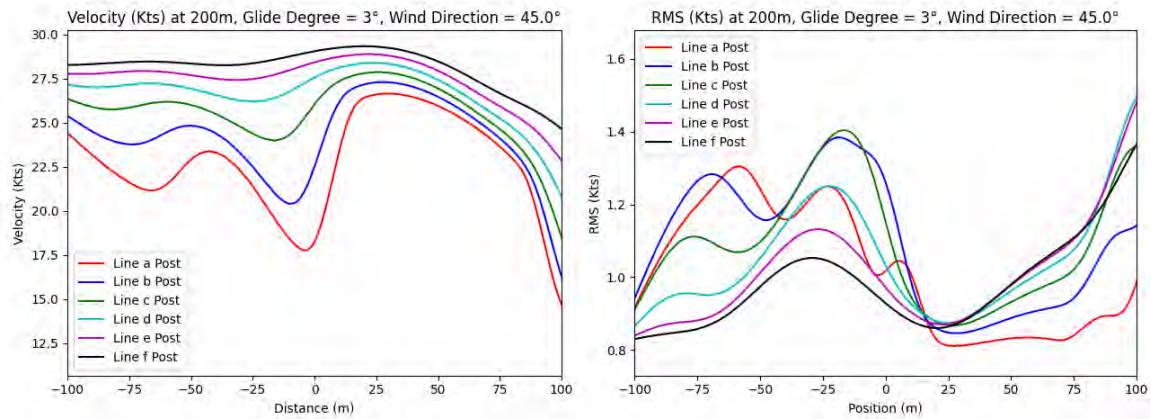


Figure 95: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

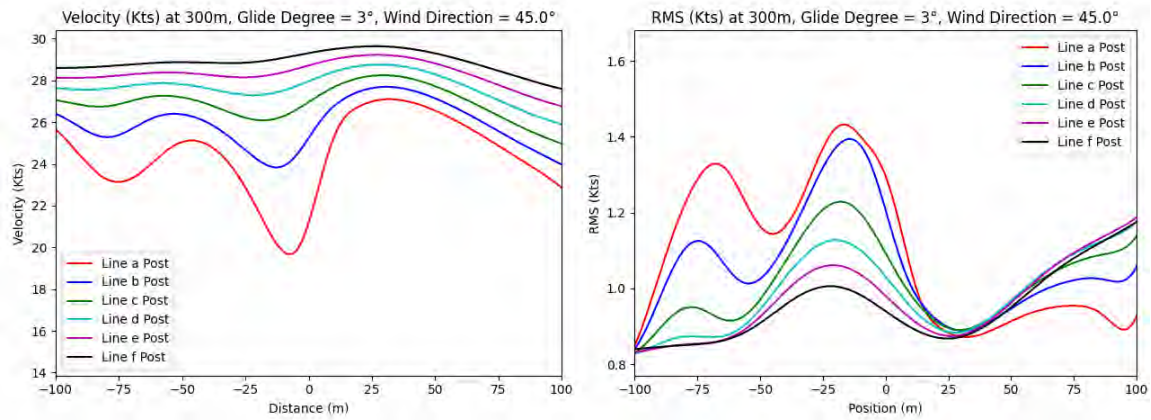


Figure 96: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

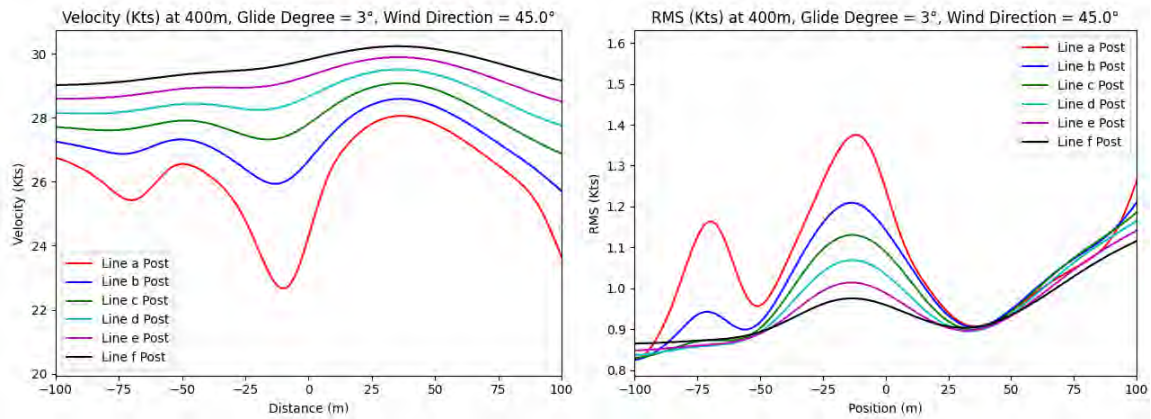


Figure 97: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

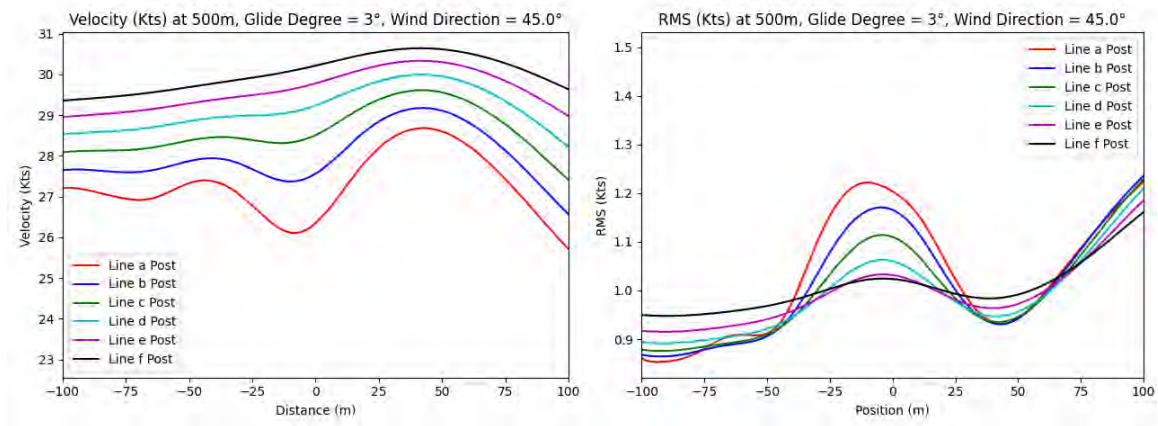


Figure 98: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

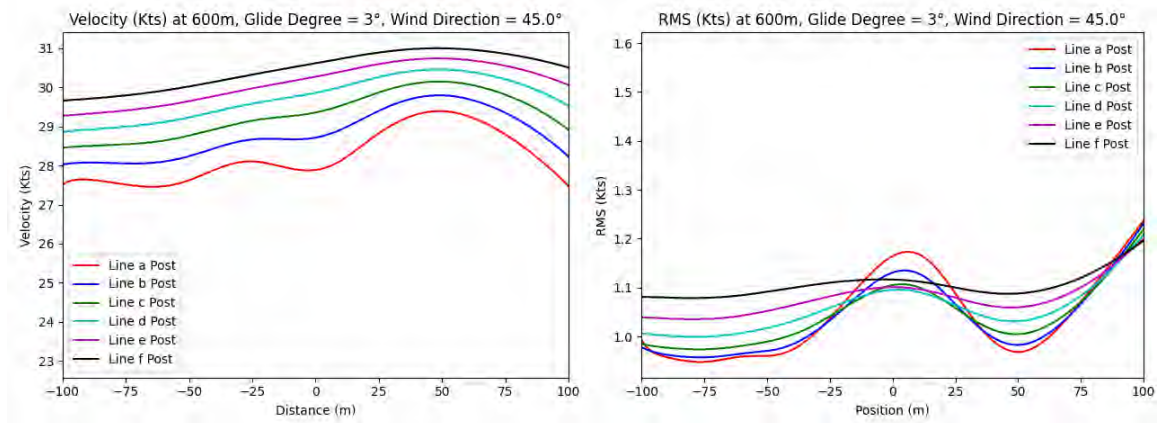


Figure 99: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

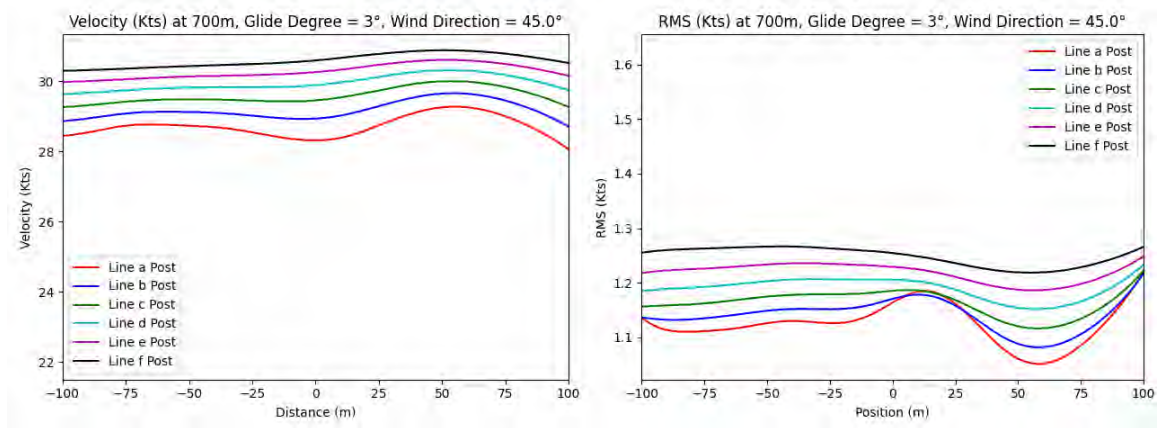


Figure 100: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

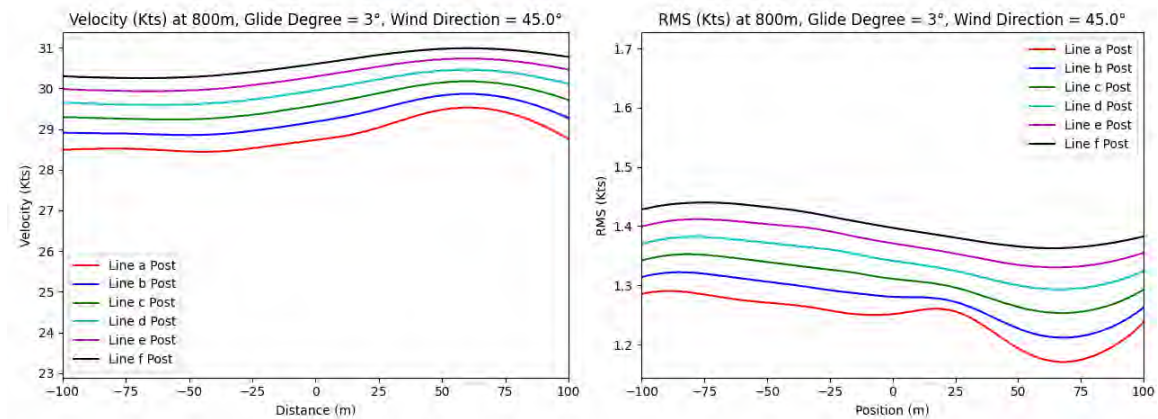


Figure 101: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

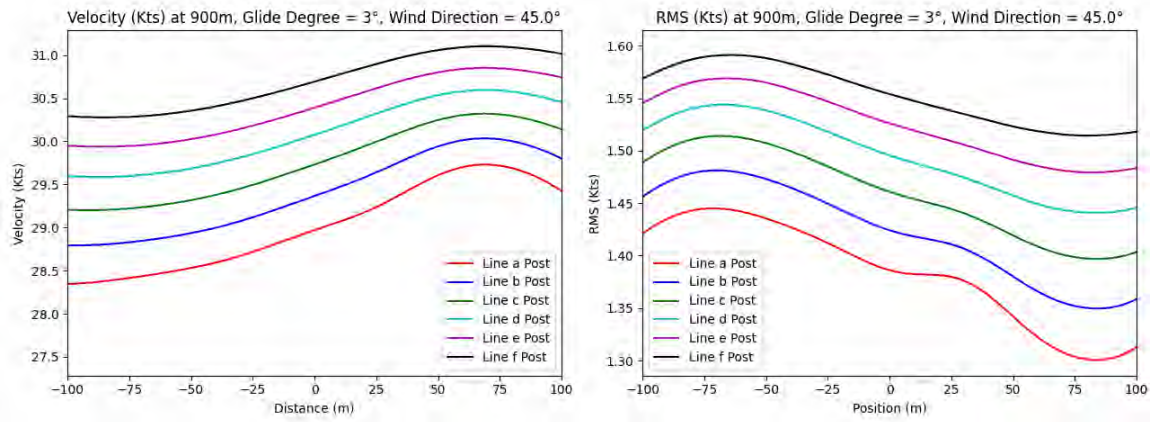


Figure 102: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 45° with 10 m/s approaching speed are shown in tables 9 and 10.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	30.52	30.63	30.67	30.69	30.72	30.77	30.83	30.83	30.69	30.75	30.75	30.78	30.41	30.12	29.91
55	30.16	30.28	30.33	30.35	30.38	30.44	30.51	30.51	30.35	30.42	30.4	30.45	30.08	29.77	29.55
50	29.8	29.94	29.99	30.01	30.04	30.1	30.19	30.18	30	30.06	30.03	30.09	29.7	29.4	29.19
45	29.41	29.56	29.61	29.63	29.67	29.73	29.82	29.81	29.59	29.62	29.57	29.67	29.26	29	28.8
40	29.01	29.15	29.2	29.21	29.24	29.31	29.4	29.37	29.11	29.09	28.99	29.14	28.73	28.55	28.37
35	28.58	28.72	28.75	28.74	28.77	28.83	28.92	28.86	28.49	28.41	28.23	28.47	28.1	28.05	27.91
30	28.13	28.24	28.25	28.22	28.22	28.26	28.32	28.2	27.71	27.52	27.25	27.63	27.34	27.48	27.39
25	27.65	27.72	27.69	27.59	27.51	27.48	27.48	27.29	26.67	26.29	25.99	26.68	26.45	26.83	26.83
20	27.1	27.11	26.97	26.7	26.39	26.12	25.94	25.59	24.72	23.39	23.65	25.7	25.42	26.11	26.19
15	26.43	26.3	25.9	25.12	24.06	23.08	22.4	21.57	20.14	17.07	17.59	23.76	24.28	25.3	25.49
10	25.46	25	23.95	22.08	20.27	19.16	18.54	17.87	16.69	13.99	13.17	17.27	23.08	24.44	24.69
5	23.78	22.77	20.83	18.75	17.87	17.66	17.67	17.53	16.97	14.92	13.9	13.35	21.71	23.33	23.63

Table 9: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 45°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	0.80273	0.78392	0.77361	0.77182	0.77761	0.79115	0.81316	0.8491	0.89427	0.95239	1.03642	1.12679	1.24085	1.35702	1.47918
55	0.82762	0.80504	0.7908	0.78523	0.7874	0.79812	0.8178	0.85153	0.8943	0.94662	1.02543	1.10792	1.21705	1.32668	1.44316
50	0.84709	0.82333	0.80738	0.79983	0.79986	0.80914	0.82798	0.86102	0.90292	0.95101	1.02511	1.09695	1.19586	1.2974	1.40744
45	0.86113	0.8387	0.82339	0.81593	0.81572	0.82521	0.84501	0.87926	0.92247	0.96934	1.04058	1.09732	1.17829	1.26841	1.37063
40	0.86793	0.84936	0.83723	0.83229	0.83439	0.84619	0.86887	0.90657	0.95425	1.00395	1.07629	1.11227	1.16651	1.24078	1.3334
35	0.86675	0.85428	0.84779	0.84795	0.85504	0.8716	0.89916	0.94234	0.99775	1.05267	1.12833	1.14052	1.16221	1.21564	1.29654
30	0.85821	0.85389	0.85558	0.86413	0.88013	0.90477	0.93926	0.98748	1.04835	1.10474	1.17814	1.17175	1.16436	1.19352	1.26061
25	0.84466	0.85082	0.8645	0.88793	0.92197	0.96167	1.00644	1.05489	1.11343	1.15868	1.20928	1.18707	1.16675	1.17297	1.22527
20	0.83047	0.8511	0.88464	0.93759	1.00867	1.07871	1.14136	1.19114	1.24559	1.28337	1.2747	1.17116	1.15746	1.1494	1.18796
15	0.82237	0.86455	0.93173	1.03165	1.1346	1.2019	1.24343	1.27209	1.29019	1.33103	1.35176	1.16586	1.12164	1.11269	1.14222
10	0.82638	0.89297	0.98306	1.04957	1.02574	0.97723	0.95026	0.95122	0.97581	1.08904	1.24302	1.20635	1.04443	1.0466	1.07652
5	0.83361	0.88501	0.88802	0.77923	0.65568	0.6334	0.67406	0.74785	0.87518	1.08464	1.31907	1.15286	0.89623	0.93039	0.9702

Table 10: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 45°

Wind Direction = 60°

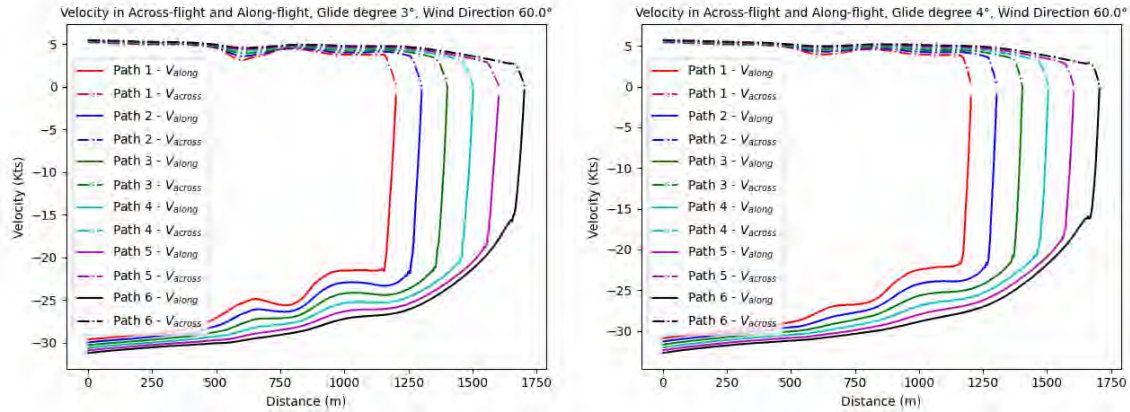


Figure 103: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 10 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 60°

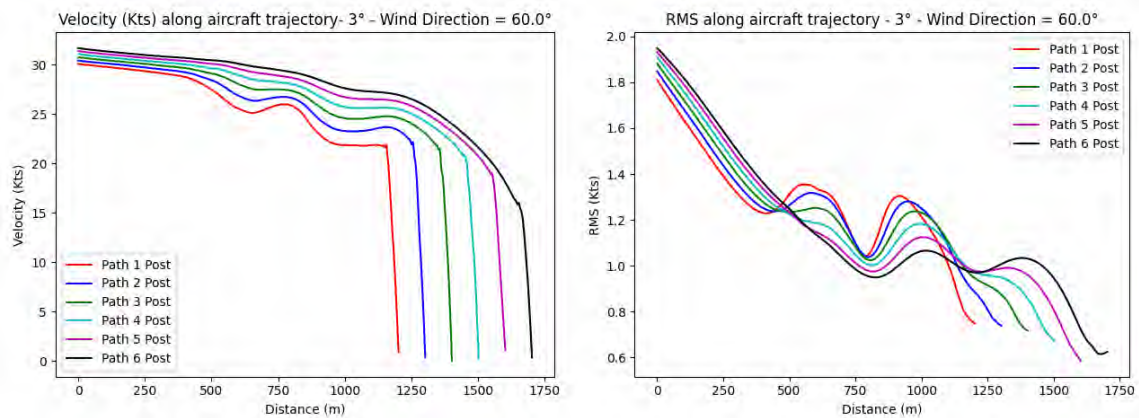


Figure 104: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 10(m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

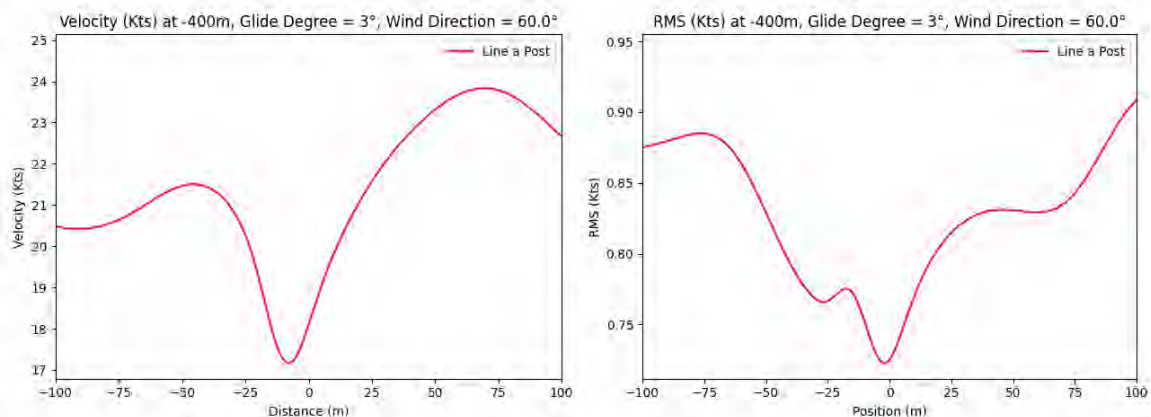


Figure 105: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

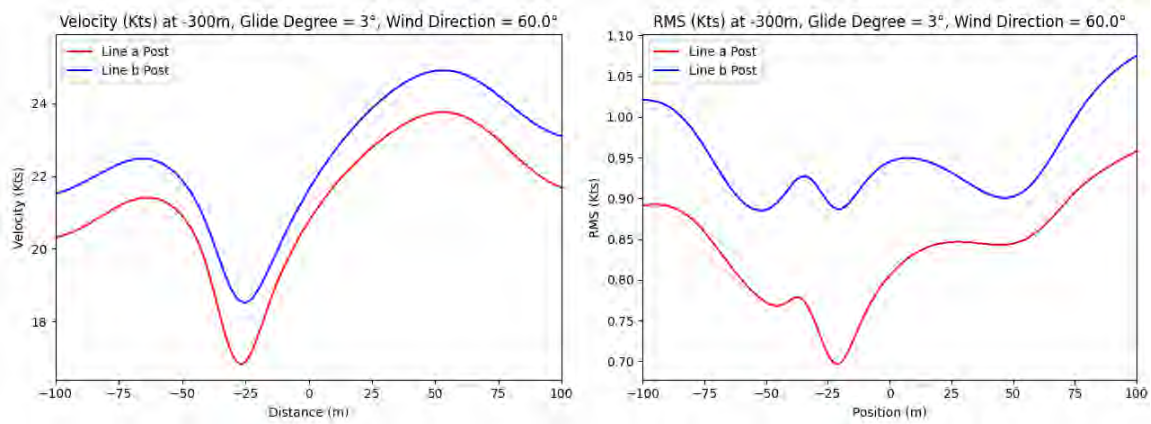


Figure 106: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

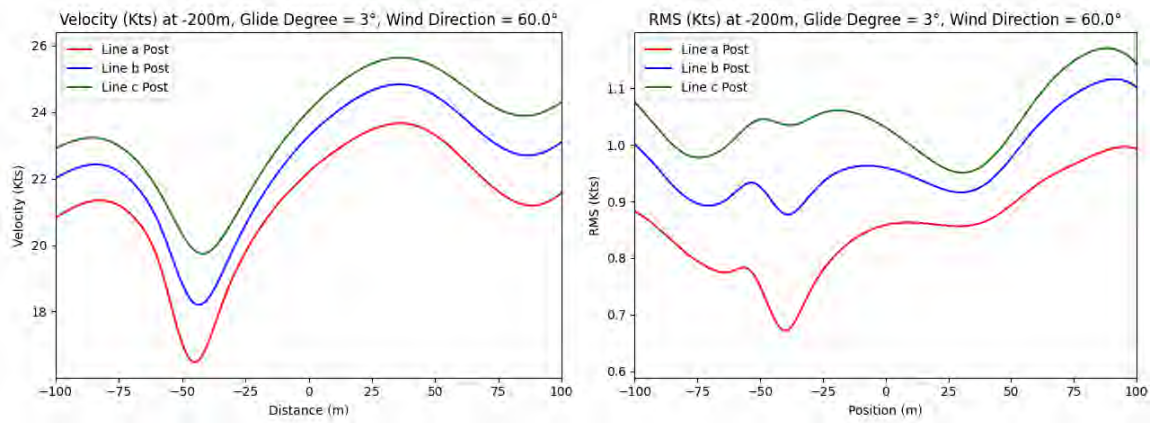


Figure 107: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

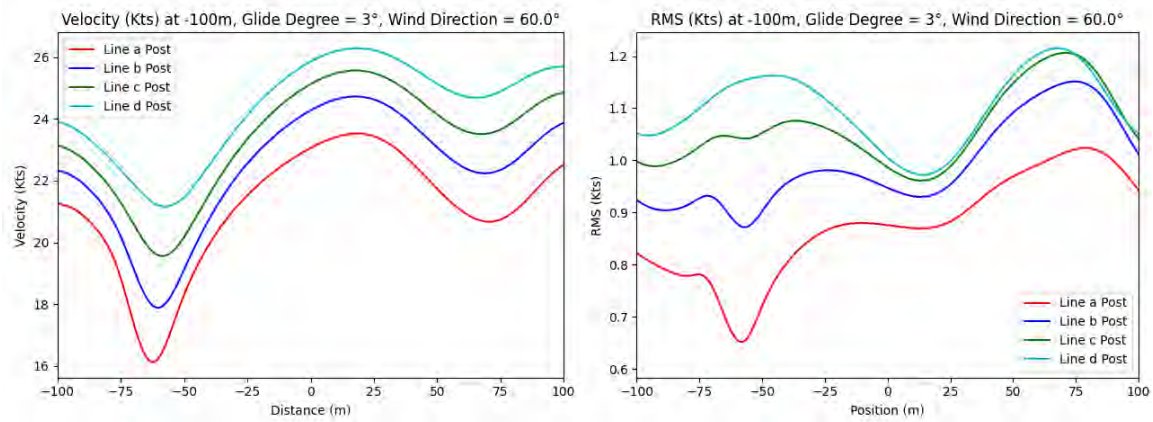


Figure 108: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

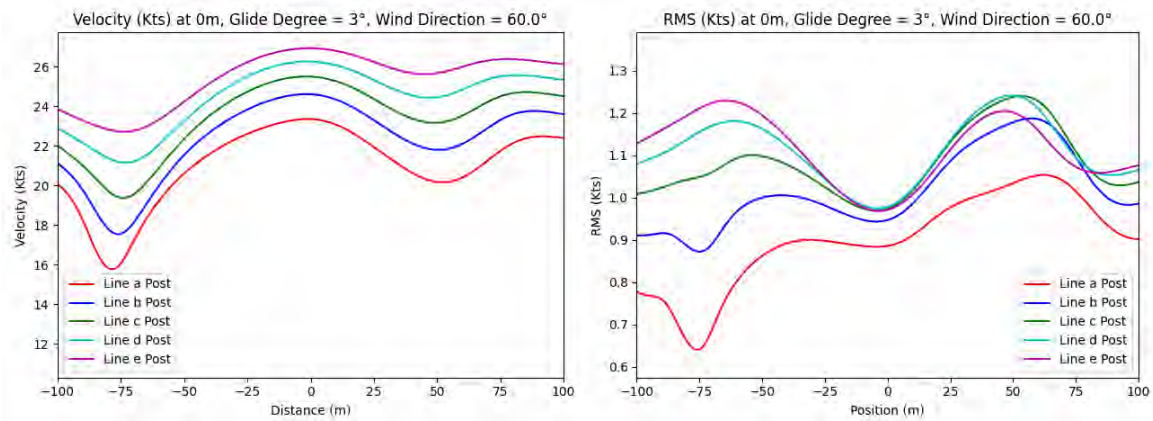


Figure 109: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

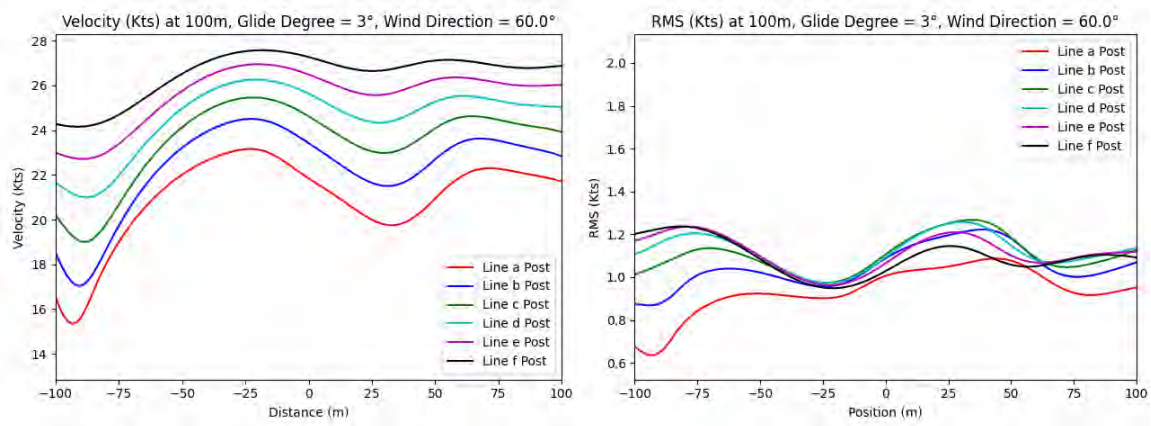


Figure 110: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

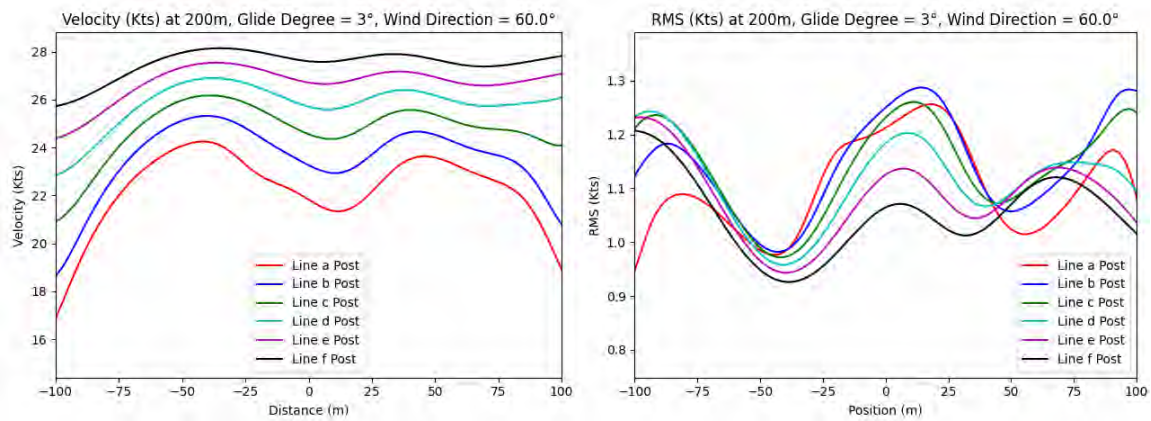


Figure 111: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

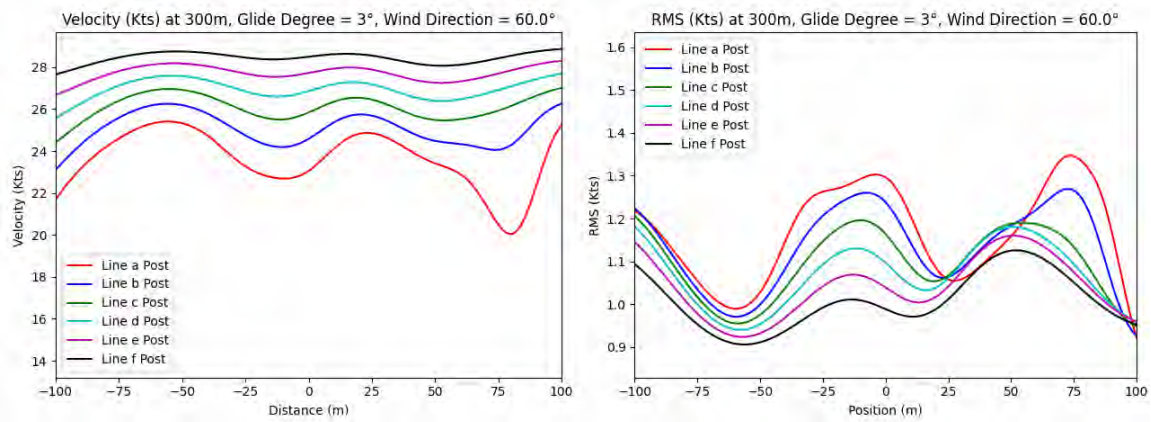


Figure 112: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

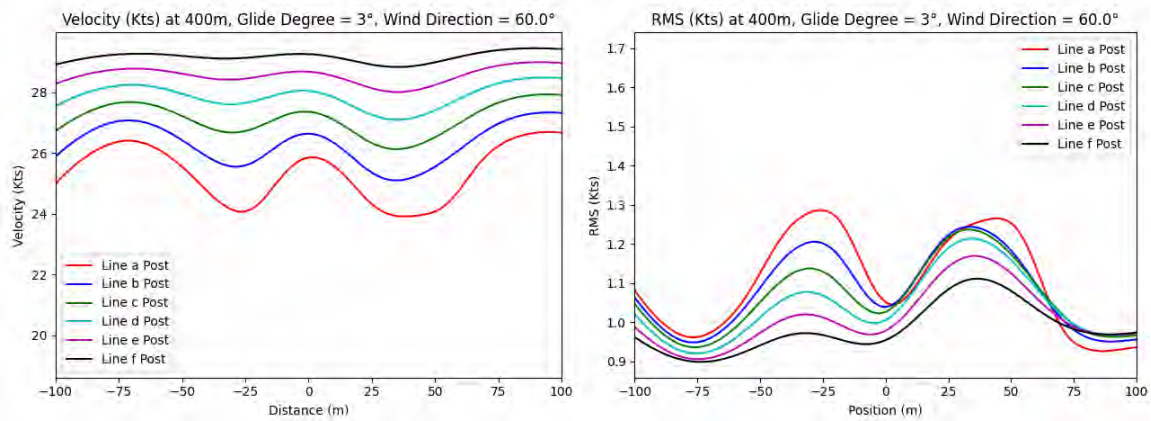


Figure 113: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

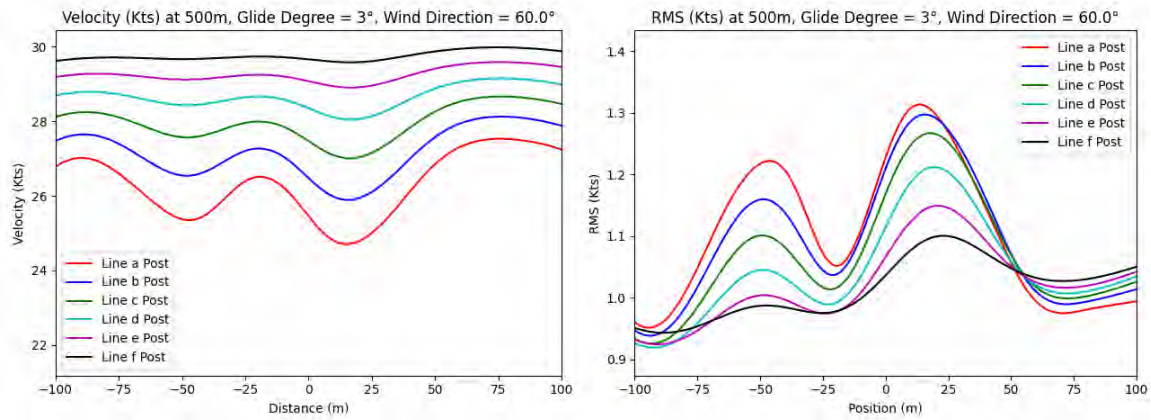


Figure 114: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

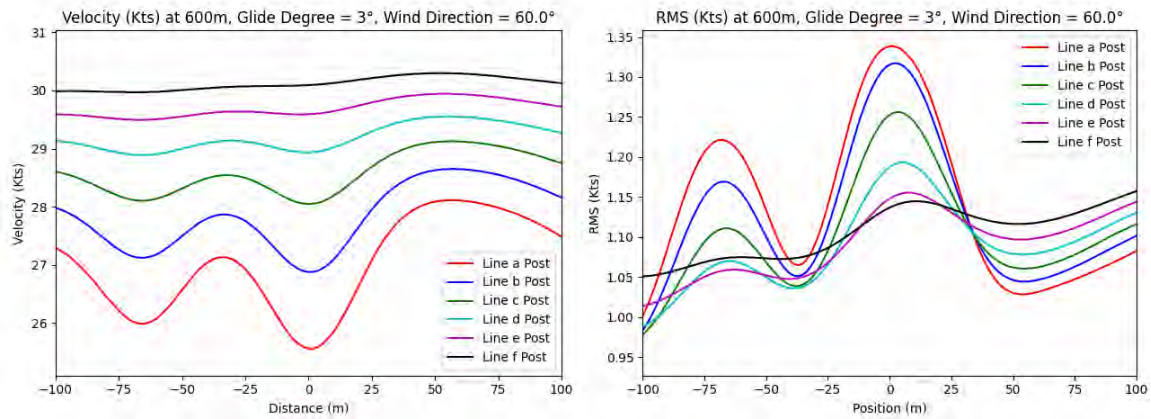


Figure 115: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

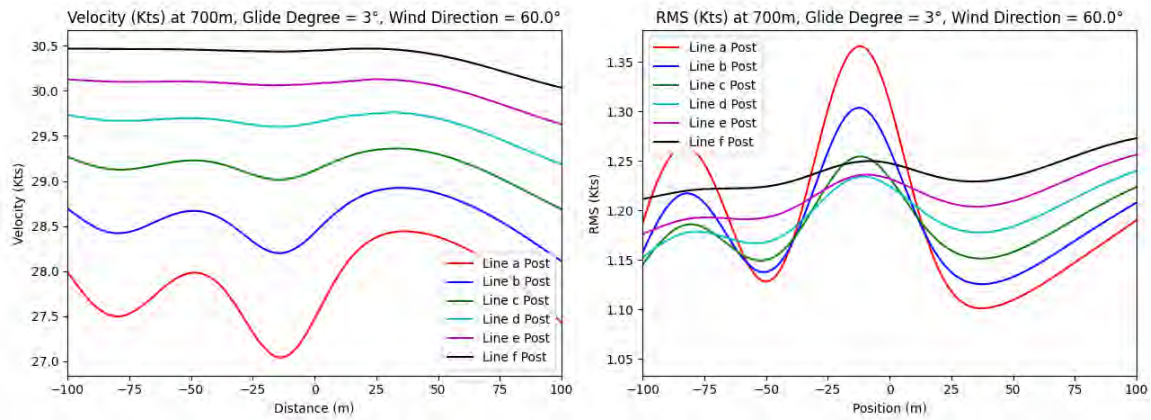


Figure 116: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

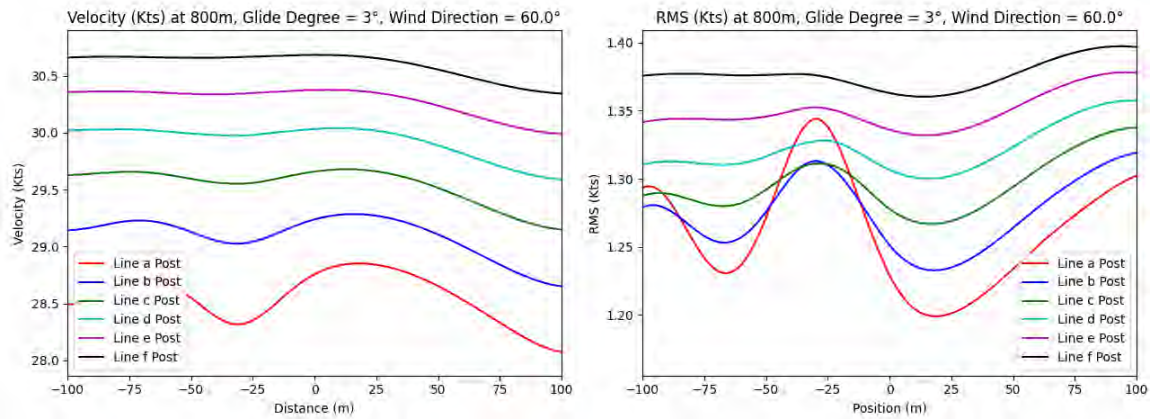


Figure 117: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

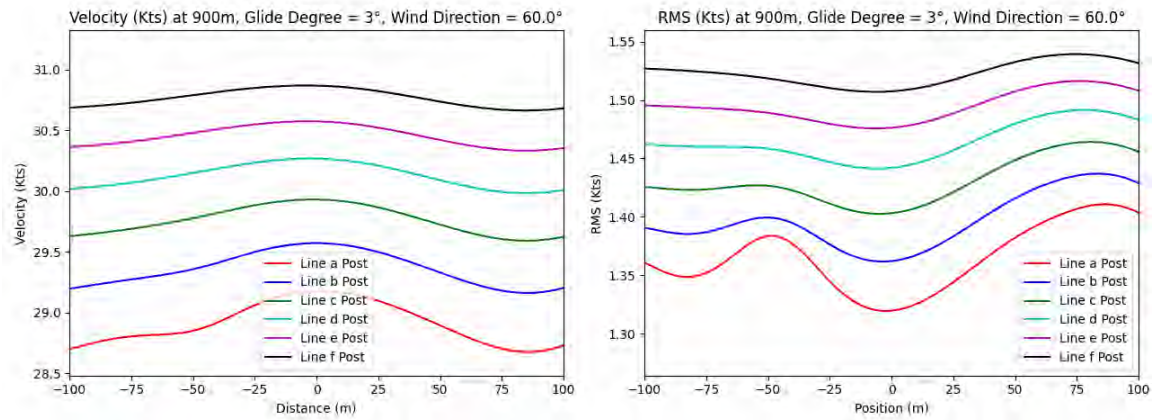


Figure 118: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 10 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 60° with 10 m/s approaching speed are shown in tables 11 and 12.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	28.9	28.98	29.29	29.71	30.03	30.22	30.3	30.33	30.39	30.39	30.36	30.31	30.25	30.21	30.11
55	28.18	28.2	28.6	29.17	29.61	29.83	29.89	29.89	29.96	29.98	29.92	29.86	29.88	29.85	29.76
50	27.45	27.39	27.87	28.6	29.17	29.44	29.47	29.42	29.49	29.54	29.42	29.32	29.42	29.48	29.4
45	26.64	26.48	27.06	27.96	28.68	29	28.98	28.83	28.91	29.03	28.81	28.61	28.86	29.05	29.01
40	25.79	25.5	26.21	27.28	28.13	28.5	28.41	28.12	28.22	28.45	28.06	27.66	28.11	28.56	28.57
35	24.9	24.48	25.35	26.6	27.56	27.96	27.77	27.33	27.46	27.83	27.18	26.47	27.1	27.99	28.09
30	24	23.42	24.5	25.93	26.98	27.39	27.07	26.46	26.59	27.17	26.22	25.2	25.91	27.32	27.54
25	23.1	22.36	23.68	25.26	26.37	26.79	26.31	25.47	25.56	26.46	25.25	23.81	24.72	26.59	26.93
20	22.21	21.3	22.9	24.59	25.72	26.13	25.47	24.35	24.3	25.69	24.26	21.37	23.6	25.86	26.24
15	21.32	20.24	22.2	23.91	25.01	25.39	24.48	23.1	22.8	24.74	23.26	16.48	22.56	25.15	25.46
10	20.38	19.19	21.52	23.17	24.18	24.52	23.31	21.71	21.1	23.37	22.41	12.21	21.65	24.45	24.54
5	19.21	18.05	20.67	22.11	22.98	23.27	21.76	20.1	19.08	21.16	21.35	13.48	20.79	23.56	23.26

Table 11: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 60°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	1.009	1.01979	0.98081	0.91328	0.85865	0.83975	0.85331	0.88129	0.90364	0.94422	1.03308	1.13885	1.23878	1.32194	1.42343
55	1.07419	1.09699	1.05117	0.96237	0.88468	0.85547	0.87022	0.89899	0.91047	0.93797	1.02966	1.13863	1.22708	1.29256	1.38315
50	1.12641	1.16342	1.11576	1.01144	0.91329	0.87401	0.89329	0.92803	0.92937	0.9441	1.04562	1.16142	1.22659	1.26602	1.34323
45	1.16534	1.21536	1.16935	1.05723	0.94402	0.89612	0.92394	0.9713	0.96243	0.96232	1.08231	1.21082	1.24296	1.24249	1.30244
40	1.18686	1.24636	1.20442	1.09215	0.97242	0.91986	0.96072	1.02518	1.00667	0.98741	1.1324	1.27702	1.2801	1.22402	1.26204
35	1.18886	1.25261	1.21753	1.11189	0.99428	0.94208	0.99963	1.0828	1.0576	1.0118	1.18146	1.3275	1.32684	1.21144	1.22359
30	1.17092	1.23236	1.2078	1.11555	1.00738	0.96029	1.03696	1.14027	1.11526	1.02972	1.21412	1.33632	1.35108	1.20123	1.18837
25	1.13382	1.18562	1.17489	1.10284	1.01139	0.97311	1.06998	1.19461	1.18245	1.0409	1.2255	1.3152	1.33388	1.18507	1.15667
20	1.07861	1.11309	1.11851	1.07254	1.00479	0.97822	1.09505	1.23674	1.25357	1.0551	1.22036	1.38667	1.27852	1.15422	1.12697
15	1.00482	1.01409	1.03865	1.02313	0.98411	0.97071	1.10439	1.24847	1.30181	1.09515	1.19362	1.45144	1.1887	1.09844	1.09369
10	0.90728	0.8853	0.93345	0.95206	0.9435	0.94279	1.08262	1.20532	1.28814	1.17669	1.13199	1.19182	1.06095	1.01135	1.04434
5	0.76784	0.71473	0.79744	0.85257	0.87195	0.8816	0.99968	1.06796	1.15859	1.211	1.08033	1.23145	0.86673	0.88188	0.95153

Table 12: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 60°

Reference Wind Speed at 10m above ground = 15m/s
Wind Direction = 30°

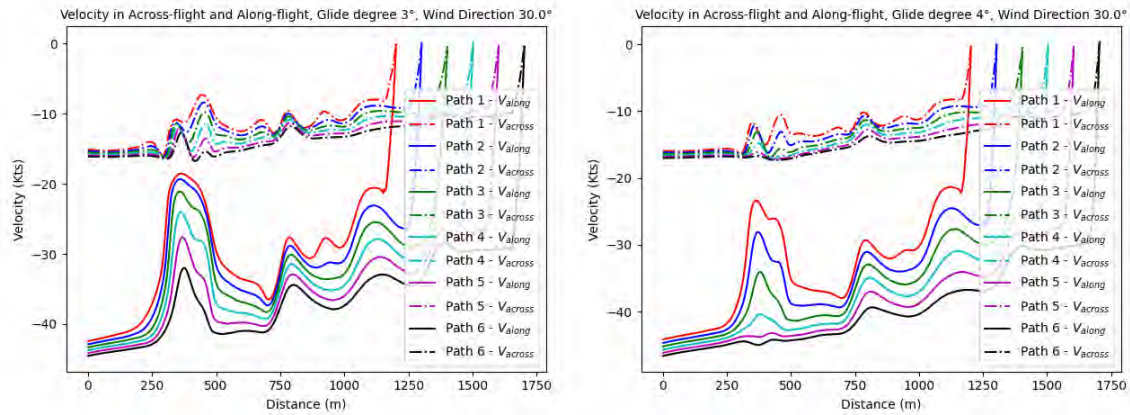


Figure 119: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 15 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 30°

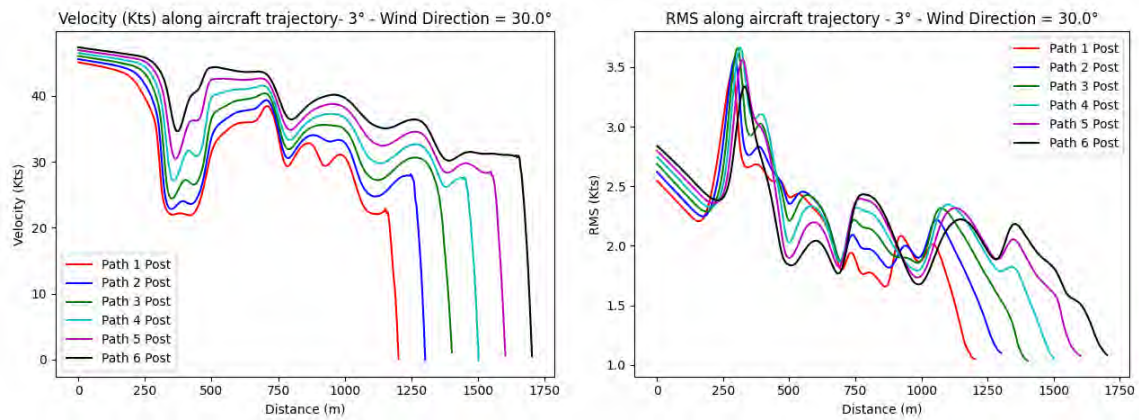


Figure 120: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 15(m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

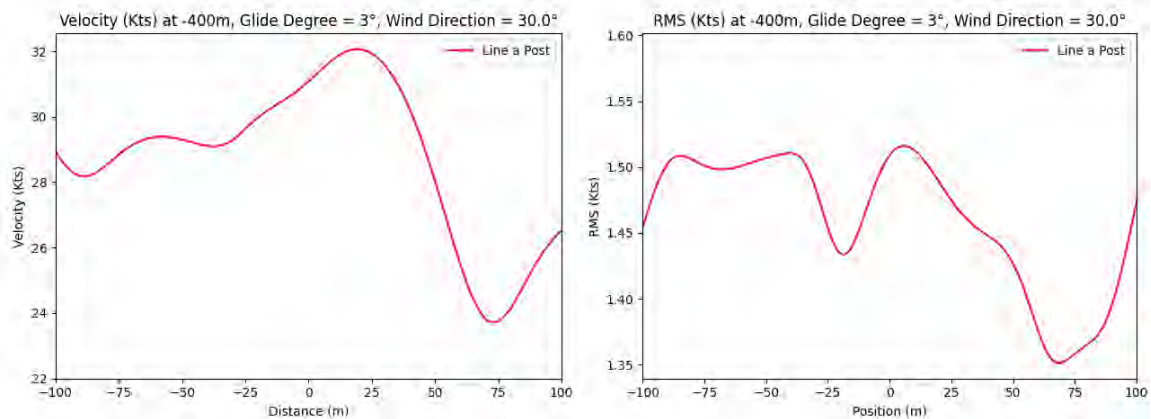


Figure 121: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

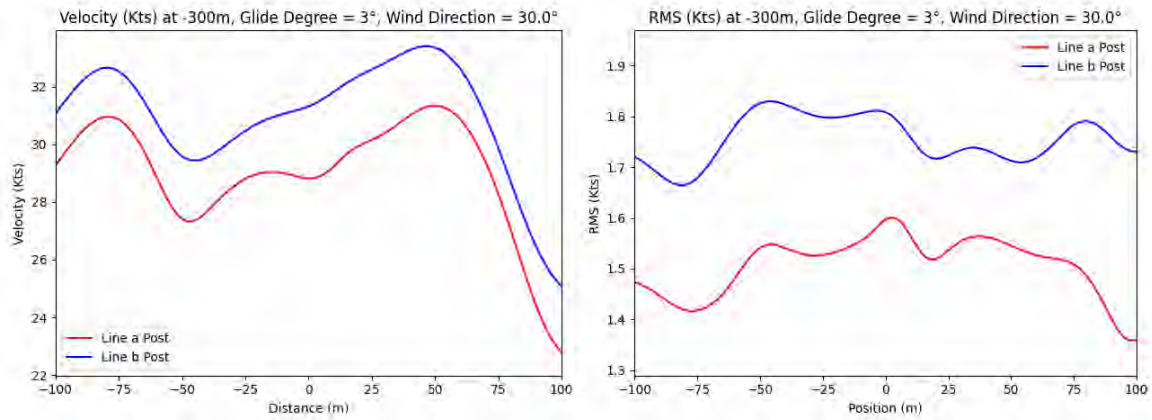


Figure 122: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

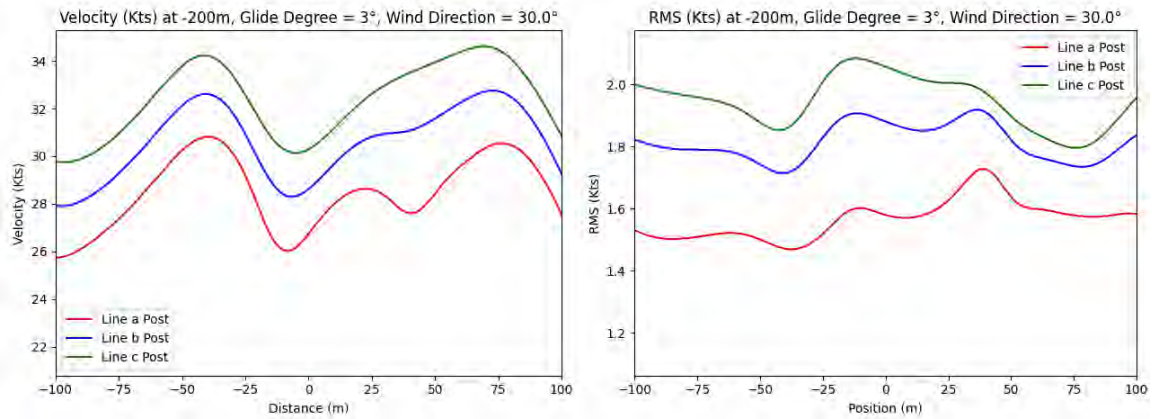


Figure 123: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

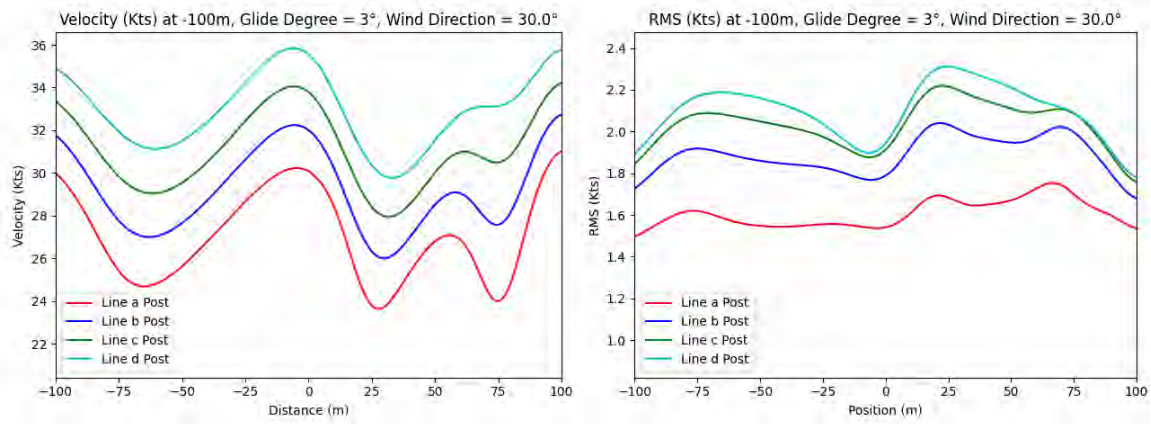


Figure 124: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

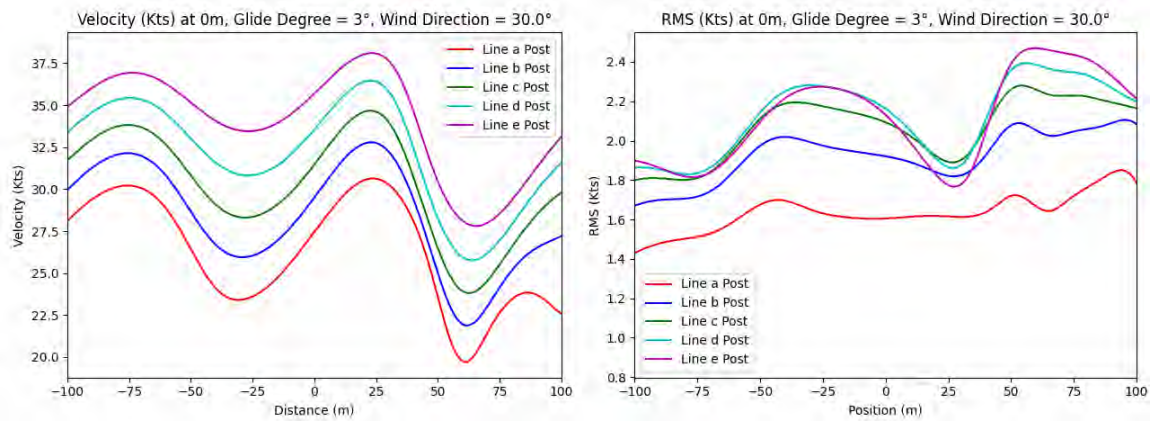


Figure 125: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

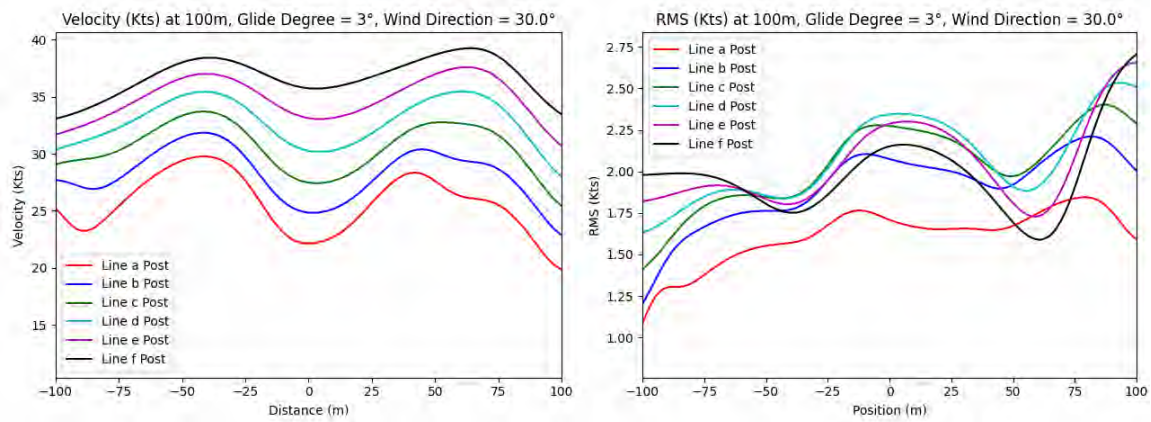


Figure 126: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

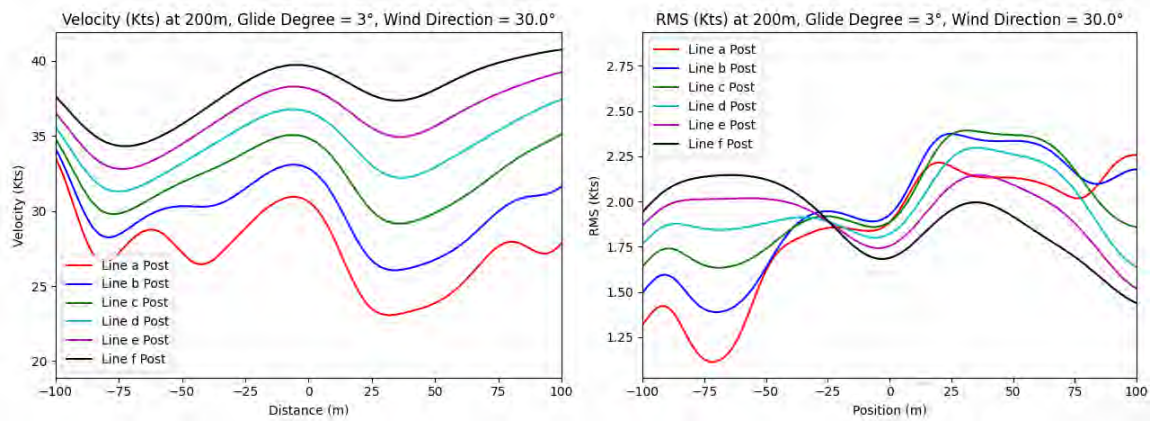


Figure 127: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

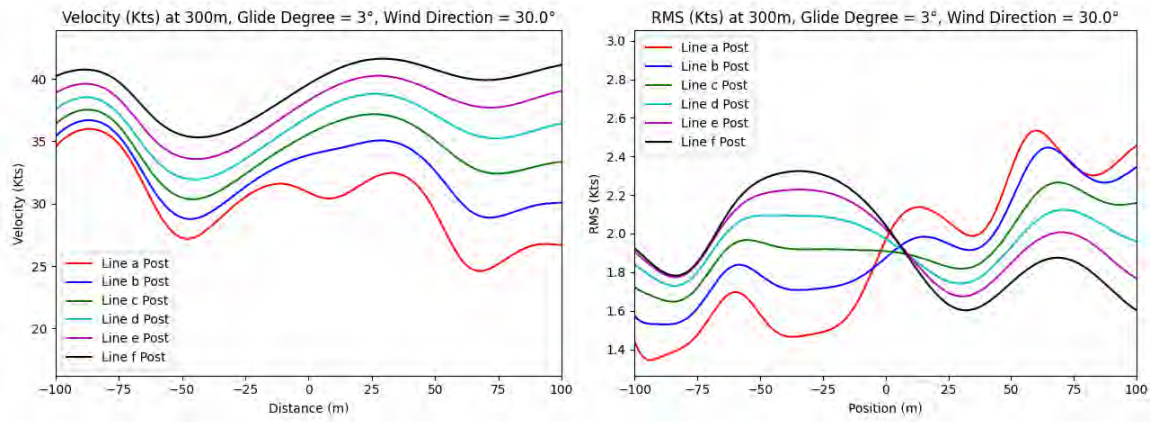


Figure 128: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

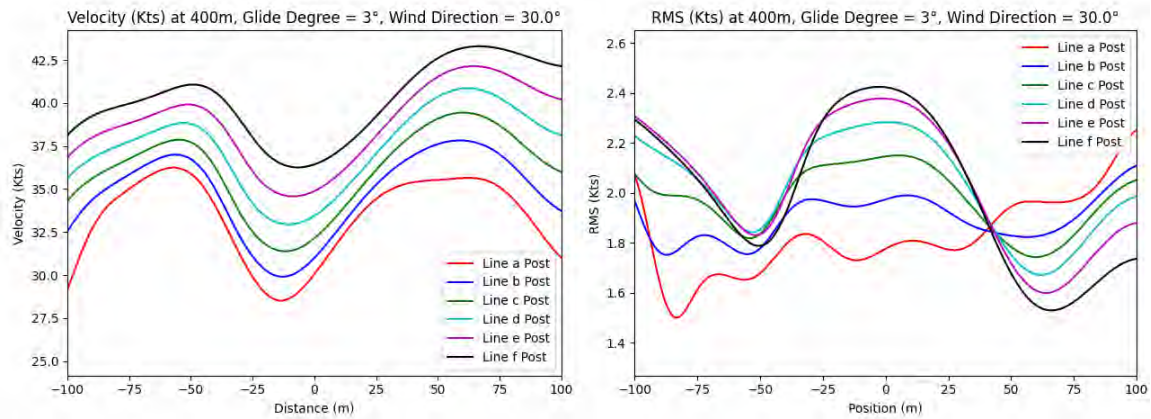


Figure 129: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

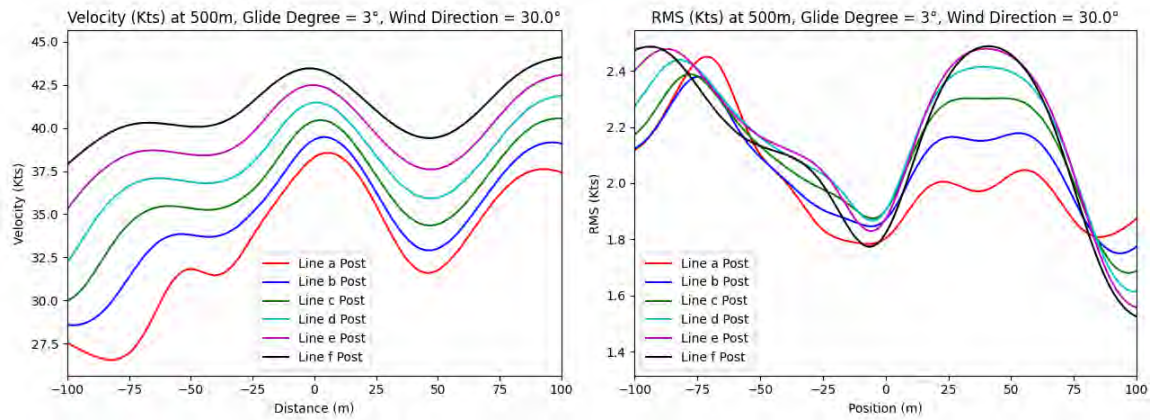


Figure 130: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

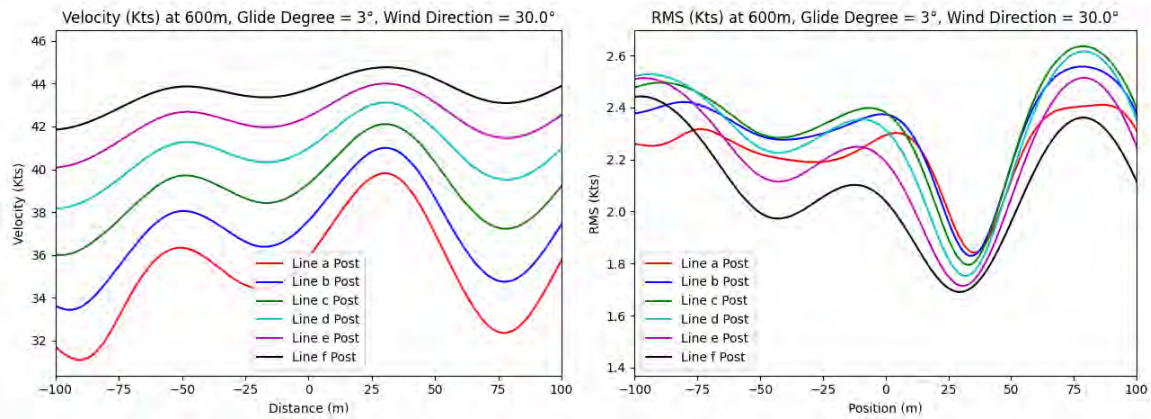


Figure 131: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

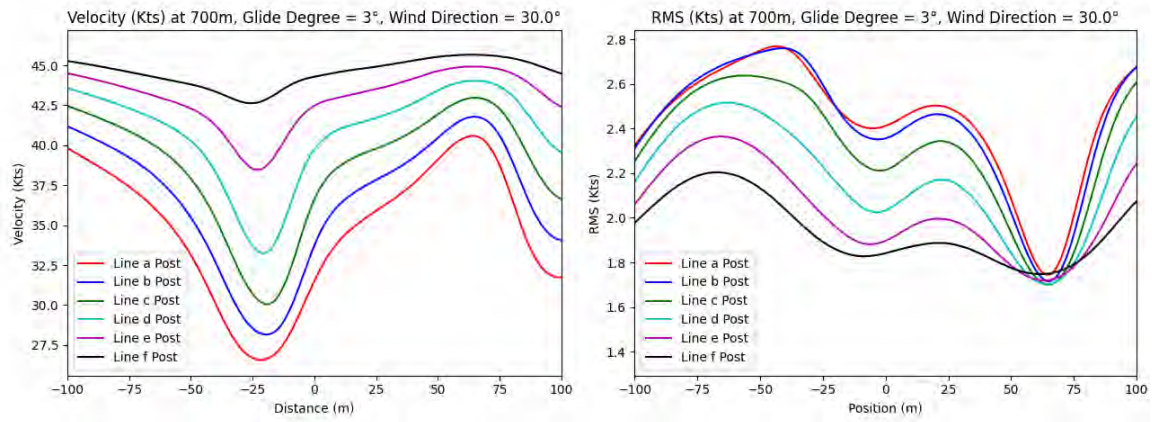


Figure 132: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

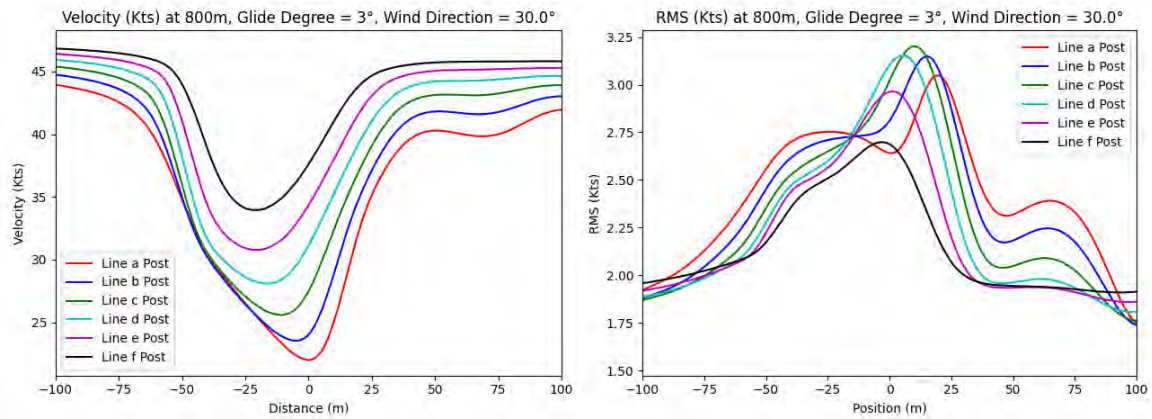


Figure 133: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

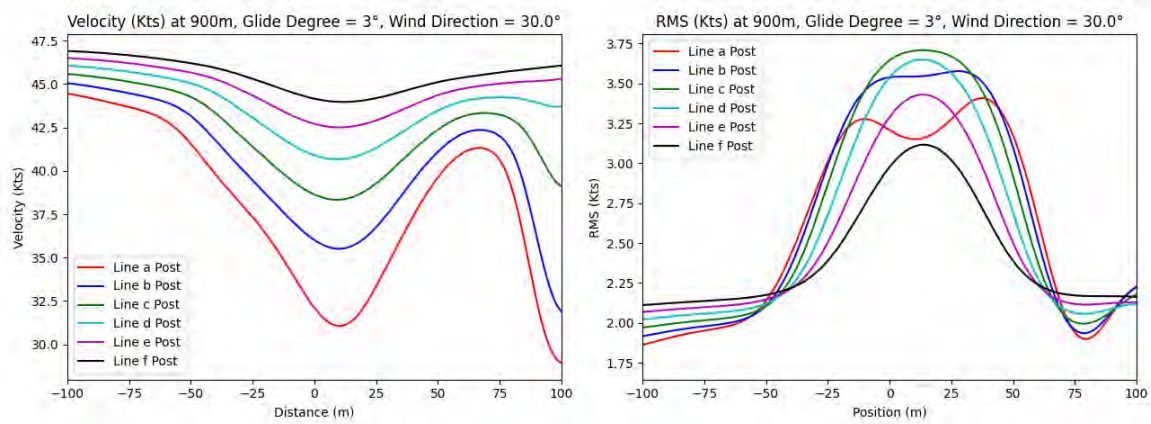


Figure 134: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 30°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 30° with 15 m/s approaching speed are shown in tables 13 and 14.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	44.04	44.87	44.47	44.1	44.99	45.05	44.71	44.89	43.91	40.87	44.74	44.31	43.28	32.72	39.86
55	42.93	44.12	43.49	42.79	44.2	44.21	43.67	44.03	42.73	38.92	43.9	43.13	41.19	29.23	37.43
50	41.8	43.34	42.48	41.38	43.35	43.26	42.45	43.07	41.56	37.31	43.02	41.81	38.35	25.62	34.58
45	40.65	42.46	41.37	39.79	42.35	42.08	40.99	41.91	40.33	35.78	42.08	40.32	35.4	23.02	30.03
40	39.51	41.48	40.18	38.14	41.2	40.67	39.3	40.59	39.09	34.34	41.08	38.69	32.87	21.69	26.24
35	38.41	40.41	38.91	36.51	39.9	39.03	37.34	39.19	37.84	33	40.05	37.03	30.93	21.2	24.81
30	37.33	39.22	37.56	34.89	38.47	37.19	35.09	37.76	36.57	31.79	39.02	35.42	29.44	21.18	24.36
25	36.29	37.91	36.13	33.26	36.92	35.19	32.51	36.24	35.22	30.74	38.05	33.92	28.17	21.39	24.57
20	35.28	36.46	34.61	31.64	35.27	33.13	29.76	34.51	33.51	29.86	37.2	32.58	27.04	21.68	25.26
15	34.27	34.88	32.97	30.05	33.57	31.15	27.13	32.55	30.3	29.16	36.49	31.44	26.04	21.94	26.25
10	33.2	33.13	31.11	28.45	31.87	29.28	24.63	30.44	24.33	28.6	35.86	30.49	25.23	22.09	27.37
5	31.76	30.93	28.67	26.64	29.99	27.3	22.04	28.23	20.2	27.89	35.08	29.57	24.63	21.93	28.37

Table 13: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 30°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	1.50197	1.28521	1.45966	1.55762	1.2487	1.29531	1.40167	1.38799	1.82685	2.28156	1.72199	1.96382	1.86591	3.05565	3.61297
55	1.63582	1.36232	1.59316	1.74535	1.30738	1.36352	1.49894	1.43512	1.92886	2.39059	1.78394	2.11891	1.95366	3.08246	3.61859
50	1.74932	1.44309	1.71712	1.91381	1.38303	1.45652	1.61581	1.49606	2.00095	2.42537	1.83928	2.25507	2.11113	2.91342	3.41592
45	1.83842	1.52929	1.83106	2.05633	1.47976	1.58265	1.75056	1.56802	2.04096	2.41078	1.88129	2.35089	2.277	2.72564	3.04982
40	1.89777	1.61407	1.92503	2.15757	1.5937	1.73823	1.89381	1.64085	2.04445	2.34894	1.90058	2.38749	2.3831	2.60184	2.76493
35	1.92629	1.69118	1.99252	2.21731	1.71554	1.9074	2.04258	1.70747	2.01376	2.24392	1.89086	2.35575	2.40907	2.50859	2.62998
30	1.92447	1.75514	2.02846	2.23829	1.82763	2.05615	2.19125	1.76959	1.95774	2.10215	1.85165	2.26018	2.3612	2.40684	2.55278
25	1.89259	1.79833	2.02948	2.21797	1.90865	2.14915	2.31022	1.83358	1.89582	1.93092	1.78216	2.1133	2.24709	2.27607	2.47998
20	1.82961	1.81041	1.9936	2.15319	1.93803	2.15918	2.34232	1.89454	1.87413	1.73745	1.68539	1.92608	2.07261	2.10919	2.38121
15	1.73246	1.77776	1.91844	2.03877	1.89696	2.07747	2.25584	1.92374	1.98435	1.52636	1.56242	1.69794	1.83535	1.90147	2.2382
10	1.59365	1.68504	1.79558	1.86058	1.7692	1.90012	2.05084	1.86816	1.9445	1.29148	1.40891	1.4173	1.52481	1.64227	2.027
5	1.38859	1.49584	1.58038	1.56032	1.52431	1.58465	1.6851	1.65313	1.39724	1.01814	1.21473	1.04491	1.11175	1.2805	1.66827

Table 14: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 30°

Wind Direction = 45°

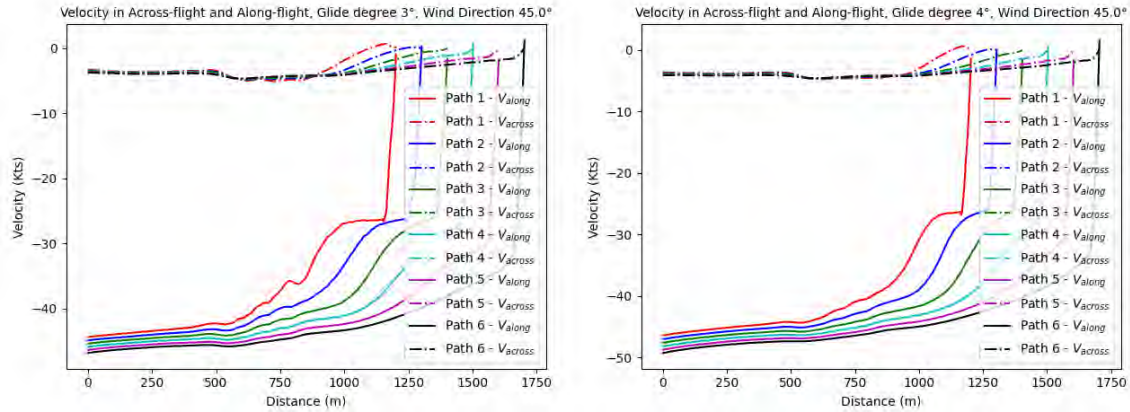


Figure 135: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 15 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 45°

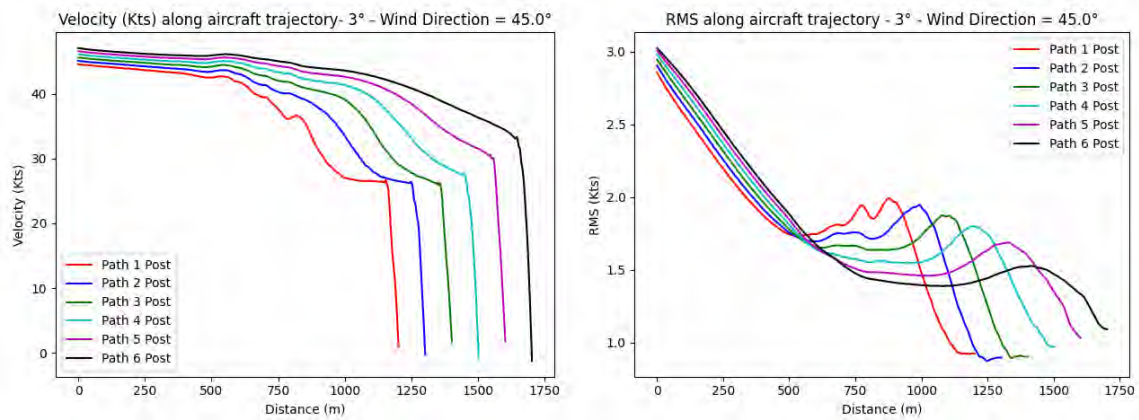


Figure 136: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 15(m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

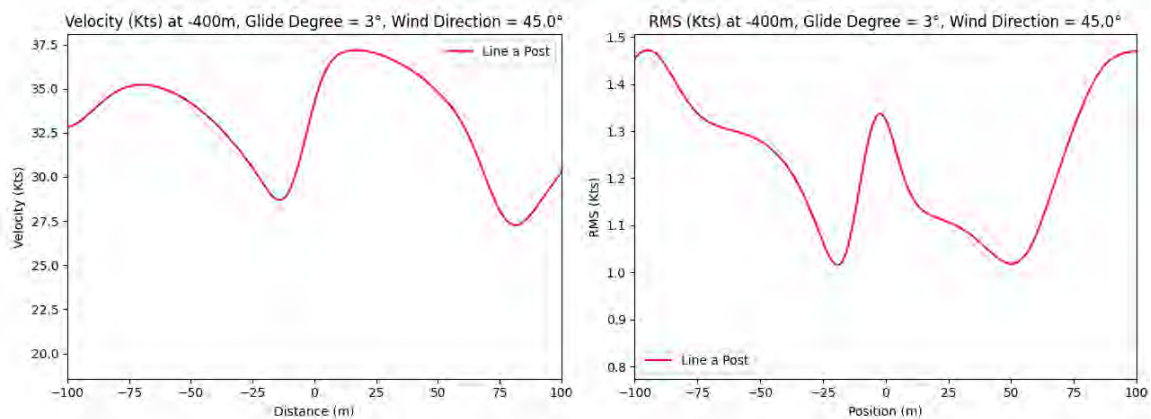


Figure 137: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

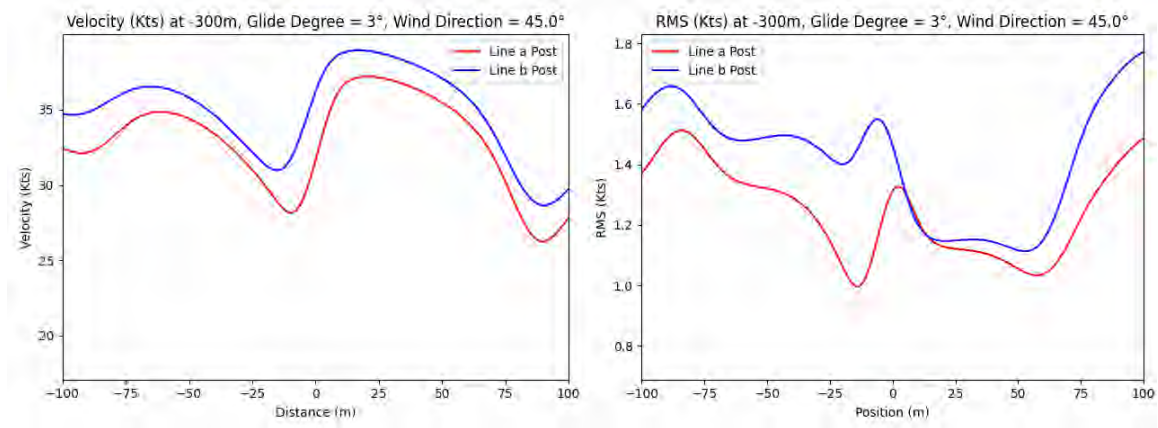


Figure 138: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

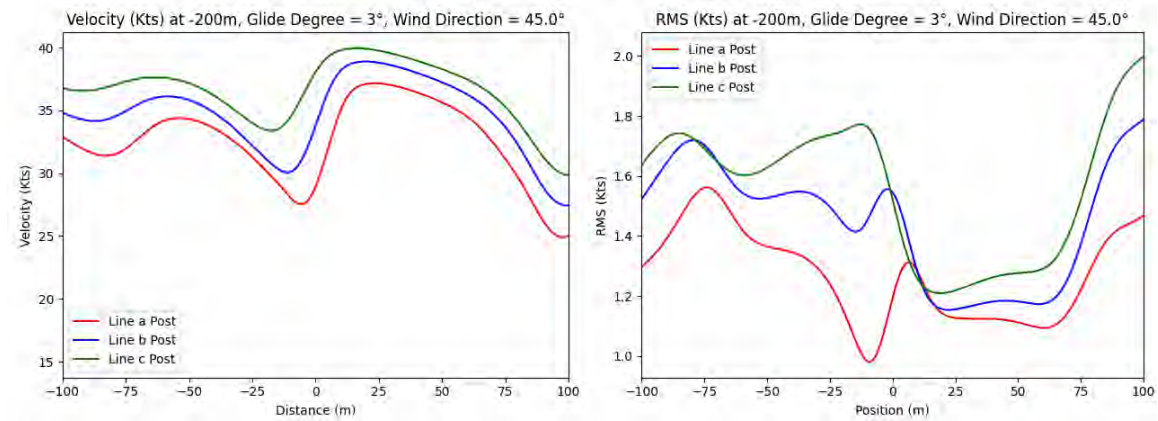


Figure 139: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

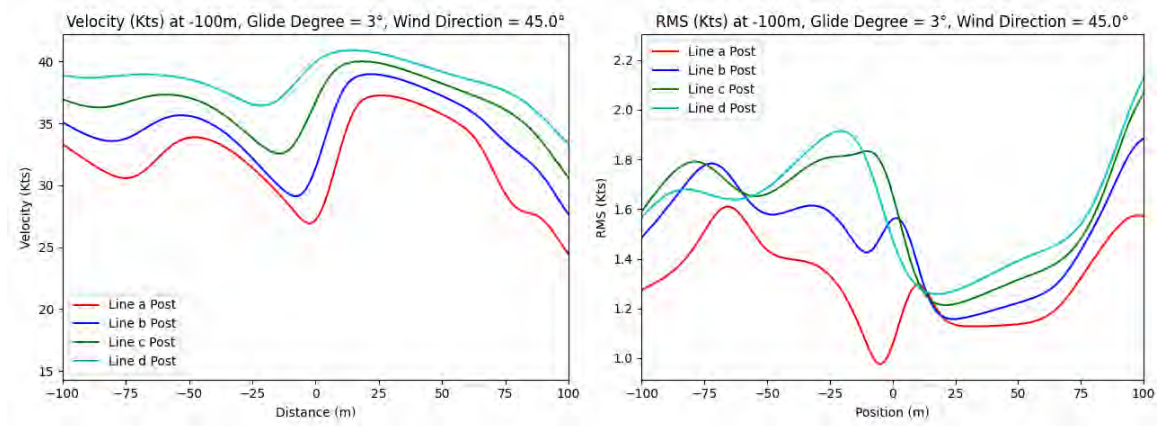


Figure 140: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

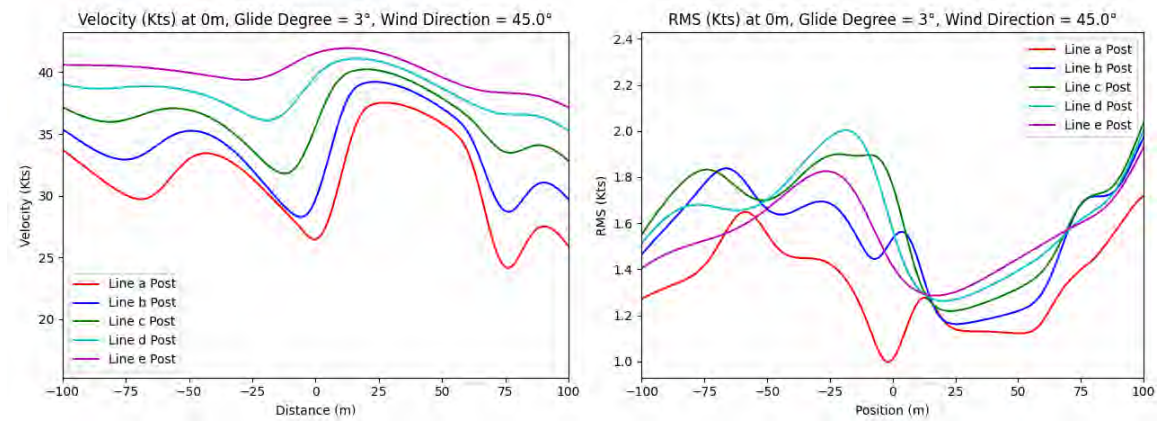


Figure 141: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

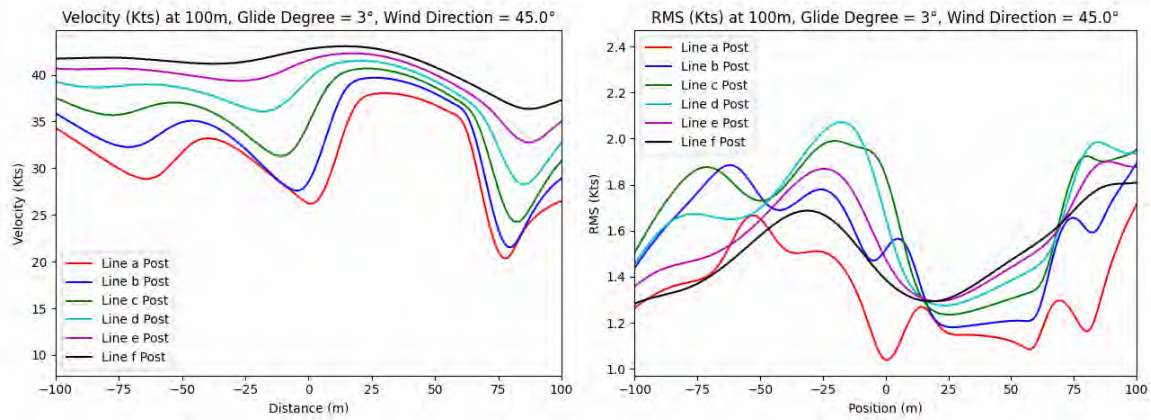


Figure 142: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

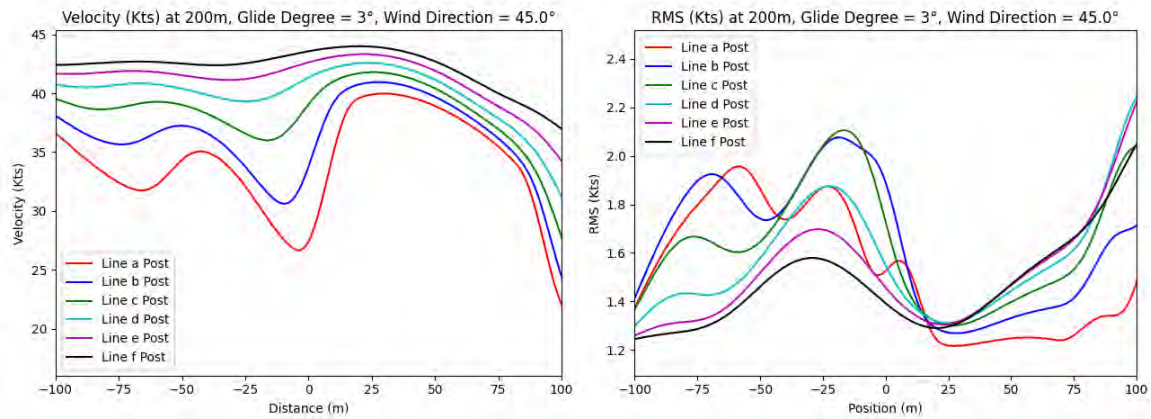


Figure 143: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

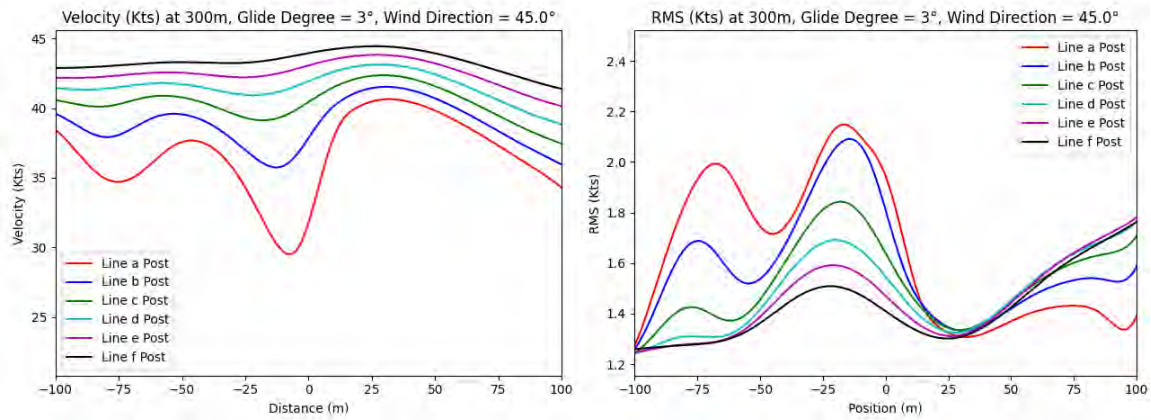


Figure 144: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

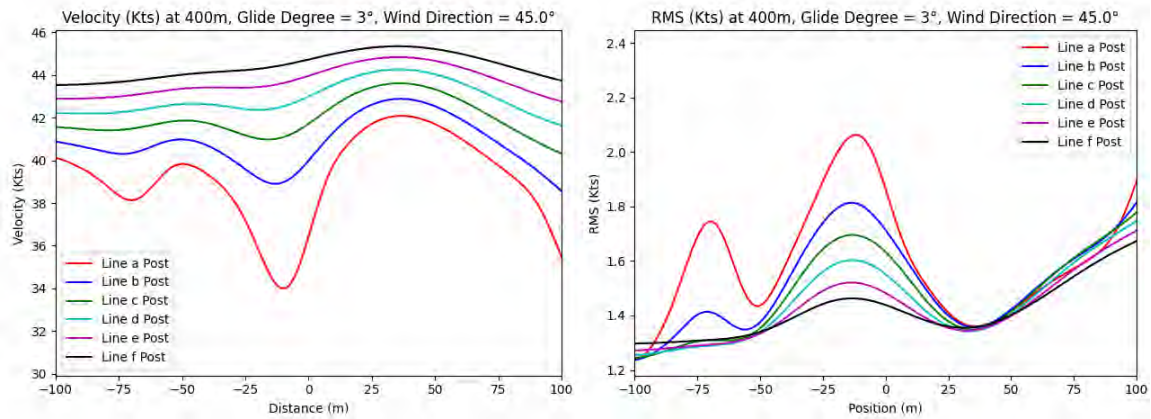


Figure 145: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

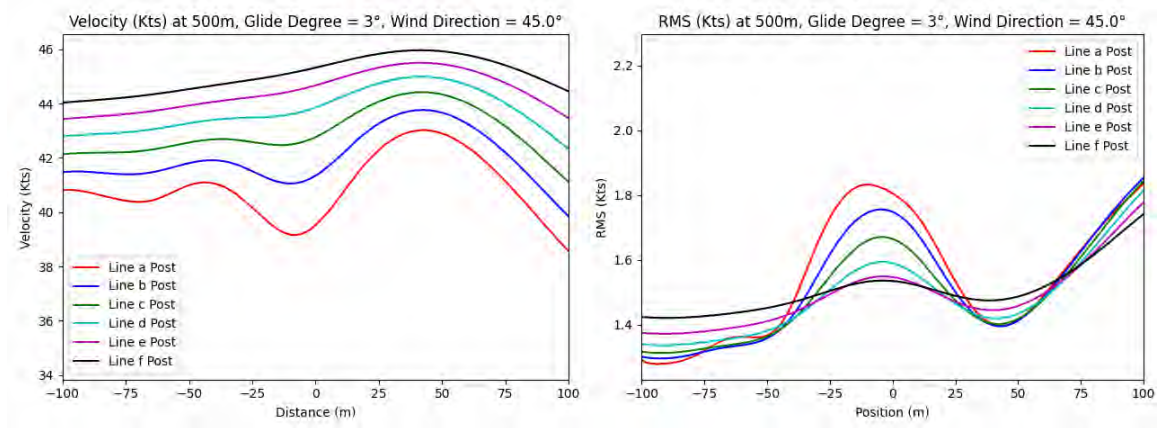


Figure 146: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

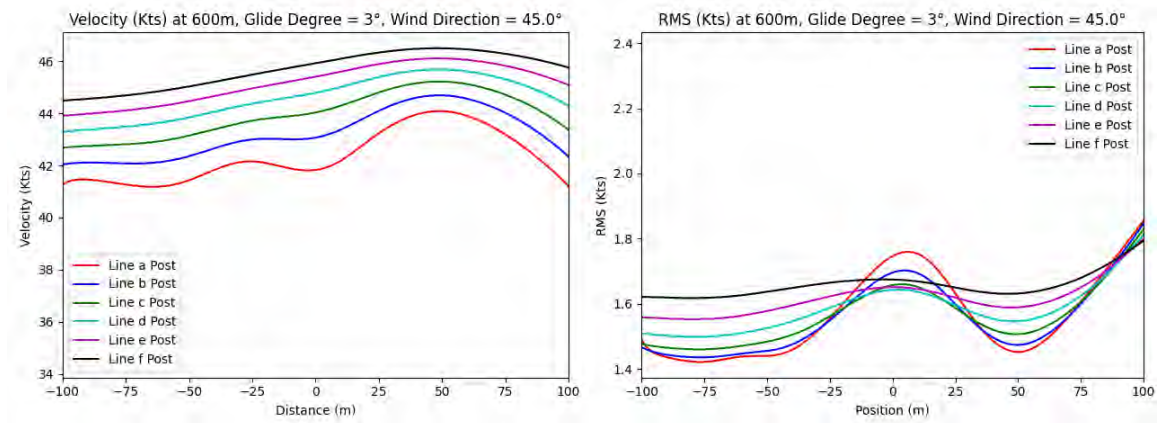


Figure 147: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

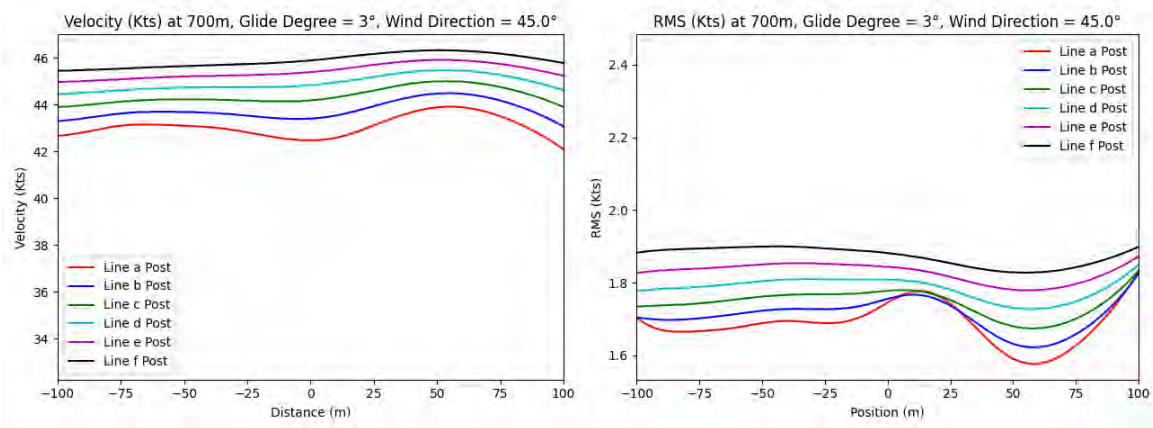


Figure 148: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

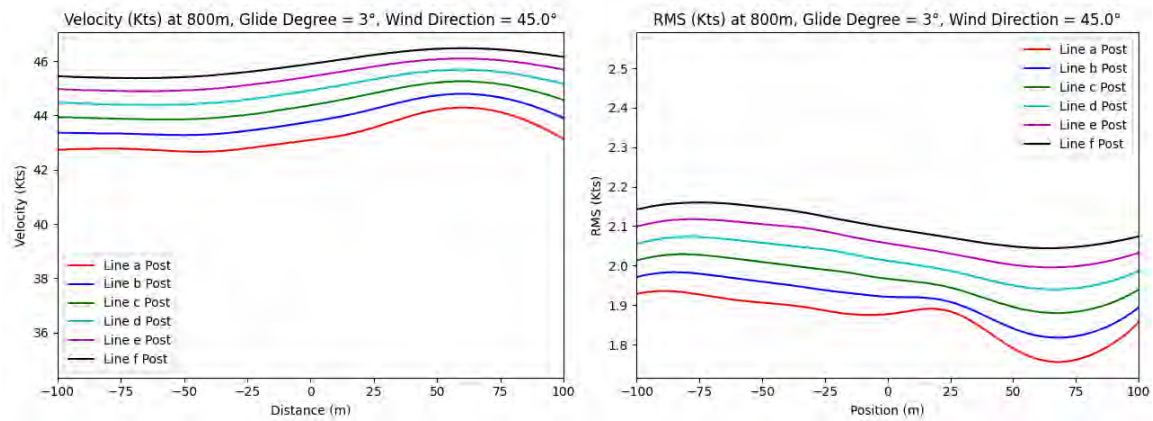


Figure 149: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

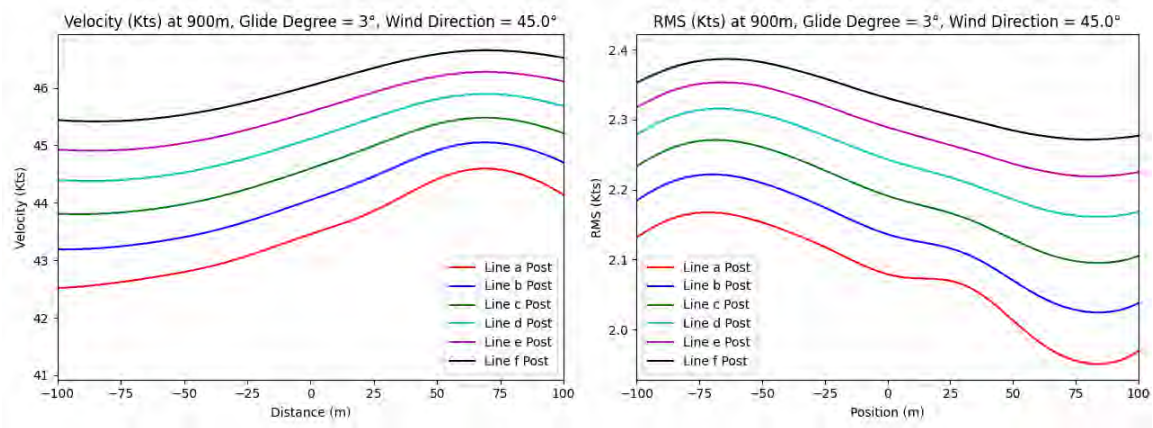


Figure 150: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 45°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 45° with 15 m/s approaching speed are shown in tables 15 and 16.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	45.78	45.95	46.01	46.03	46.08	46.15	46.25	46.25	46.04	46.13	46.13	46.17	45.62	45.19	44.86
55	45.23	45.42	45.5	45.52	45.57	45.65	45.77	45.77	45.53	45.63	45.6	45.68	45.12	44.65	44.33
50	44.7	44.91	44.98	45.01	45.07	45.15	45.28	45.28	45	45.08	45.04	45.14	44.55	44.11	43.78
45	44.12	44.34	44.42	44.44	44.5	44.59	44.73	44.71	44.39	44.43	44.36	44.5	43.88	43.5	43.2
40	43.51	43.73	43.8	43.81	43.86	43.96	44.1	44.06	43.66	43.64	43.49	43.72	43.09	42.83	42.56
35	42.87	43.08	43.13	43.11	43.15	43.25	43.38	43.28	42.74	42.61	42.34	42.71	42.15	42.08	41.86
30	42.19	42.37	42.38	42.33	42.33	42.39	42.48	42.3	41.56	41.29	40.88	41.45	41.01	41.22	41.09
25	41.47	41.58	41.53	41.38	41.27	41.21	41.21	40.93	40	39.44	38.99	40.02	39.67	40.25	40.24
20	40.65	40.67	40.45	40.05	39.59	39.17	38.9	38.38	37.08	35.09	35.48	38.55	38.13	39.16	39.29
15	39.65	39.44	38.84	37.67	36.09	34.62	33.59	32.35	30.22	25.6	26.38	35.64	36.42	37.96	38.23
10	38.19	37.51	35.92	33.12	30.41	28.74	27.81	26.8	25.03	20.98	19.76	25.9	34.61	36.66	37.03
5	35.67	34.15	31.24	28.13	26.81	26.5	26.5	26.29	25.45	22.37	20.85	20.03	32.56	35	35.44

Table 15: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 45°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	1.20409	1.17588	1.16041	1.15773	1.16641	1.18672	1.21974	1.27366	1.34141	1.42859	1.55464	1.69019	1.86128	2.03553	2.21878
55	1.24142	1.20756	1.1862	1.17784	1.1811	1.19717	1.2267	1.2773	1.34144	1.41993	1.53814	1.66189	1.82557	1.99002	2.16474
50	1.27063	1.23499	1.21107	1.19974	1.1998	1.21371	1.24196	1.29154	1.35437	1.42651	1.53767	1.64542	1.79379	1.94611	2.11116
45	1.29169	1.25804	1.23508	1.22389	1.22358	1.23782	1.26751	1.31889	1.3837	1.454	1.56087	1.64598	1.76744	1.90261	2.05594
40	1.3019	1.27403	1.25584	1.24844	1.25159	1.26928	1.3033	1.35985	1.43138	1.50592	1.61444	1.6684	1.74977	1.86117	2.00011
35	1.30012	1.28142	1.27168	1.27192	1.28256	1.30739	1.34874	1.4135	1.49663	1.579	1.6925	1.71077	1.74332	1.82346	1.94481
30	1.28732	1.28083	1.28337	1.2962	1.32019	1.35715	1.40888	1.48122	1.57253	1.65712	1.76721	1.75762	1.74654	1.79029	1.89092
25	1.26699	1.27624	1.29675	1.33189	1.38295	1.44251	1.50967	1.58233	1.67014	1.73801	1.81392	1.7806	1.75013	1.75946	1.83791
20	1.2457	1.27664	1.32695	1.40639	1.51301	1.61806	1.71205	1.78671	1.86838	1.92506	1.91205	1.75674	1.73619	1.7241	1.78195
15	1.23355	1.29683	1.3976	1.54748	1.7019	1.80285	1.86514	1.90813	1.93528	1.99654	2.02764	1.74879	1.68246	1.66904	1.71333
10	1.23957	1.33946	1.47459	1.57436	1.53861	1.46584	1.42539	1.42682	1.46372	1.63356	1.86454	1.80952	1.56664	1.5699	1.61477
5	1.25041	1.32751	1.33203	1.16885	0.98351	0.9501	1.01109	1.12178	1.31277	1.62696	1.9786	1.72929	1.34435	1.39559	1.45529

Table 16: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 45°

Wind Direction = 60°

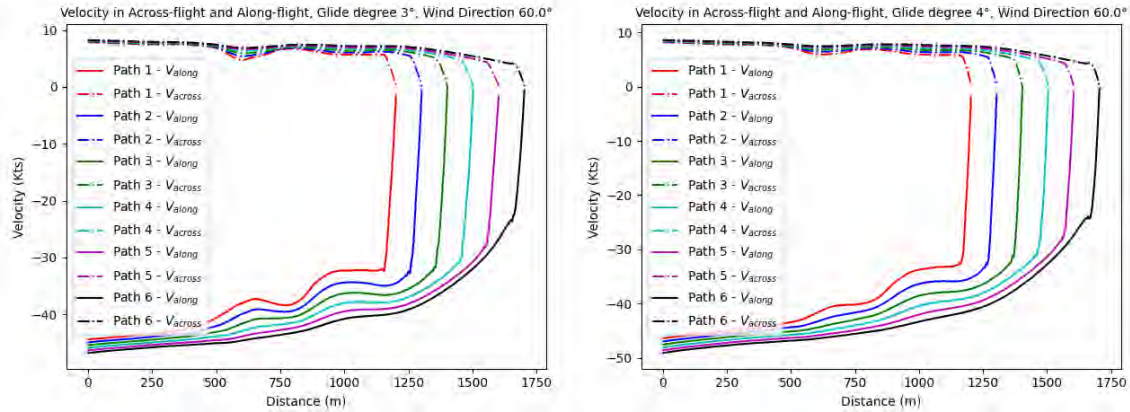


Figure 151: Wind Speed in the along-flight and across-flight directions along a possible Critical Aircraft Trajectory (Figure 19). Approaching wind speed 15 (m/s) - Landing/Takeoff 3° and 4° - Wind Direction 60°

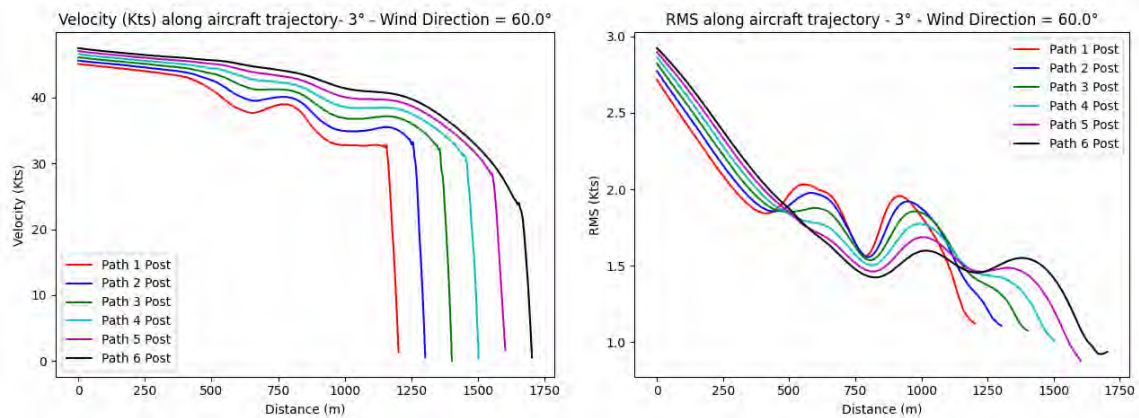


Figure 152: Velocity magnitude (Kts) and RMS (Kts) along a possible Critical Aircraft Trajectory. Reference wind speed 15(m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

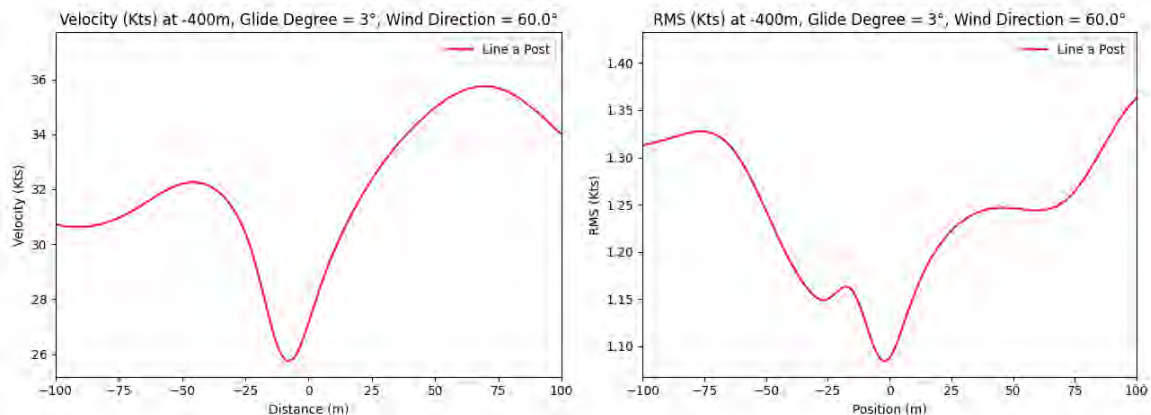


Figure 153: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

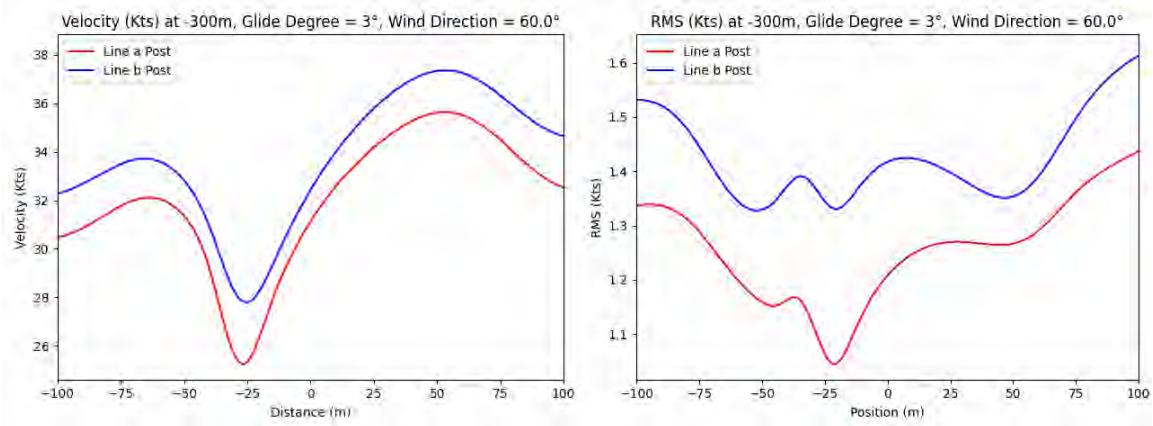


Figure 154: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

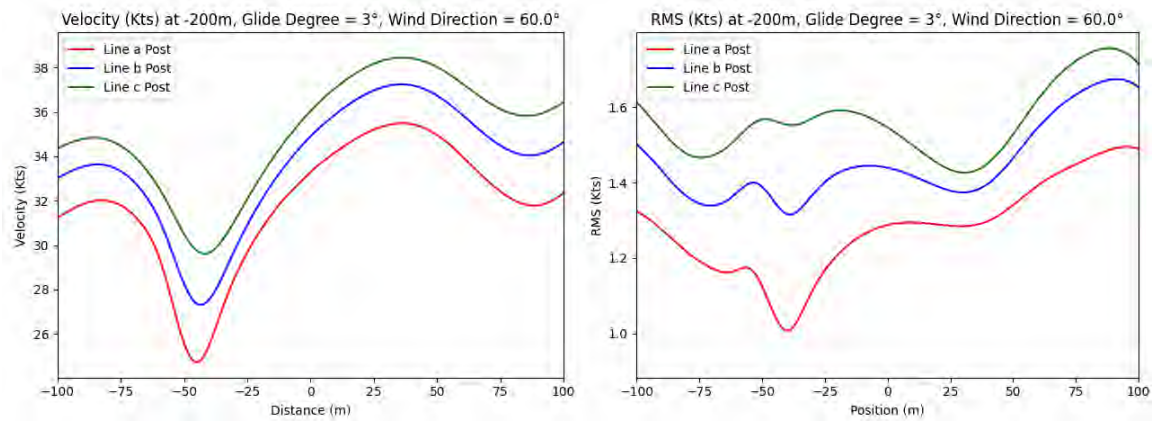


Figure 155: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

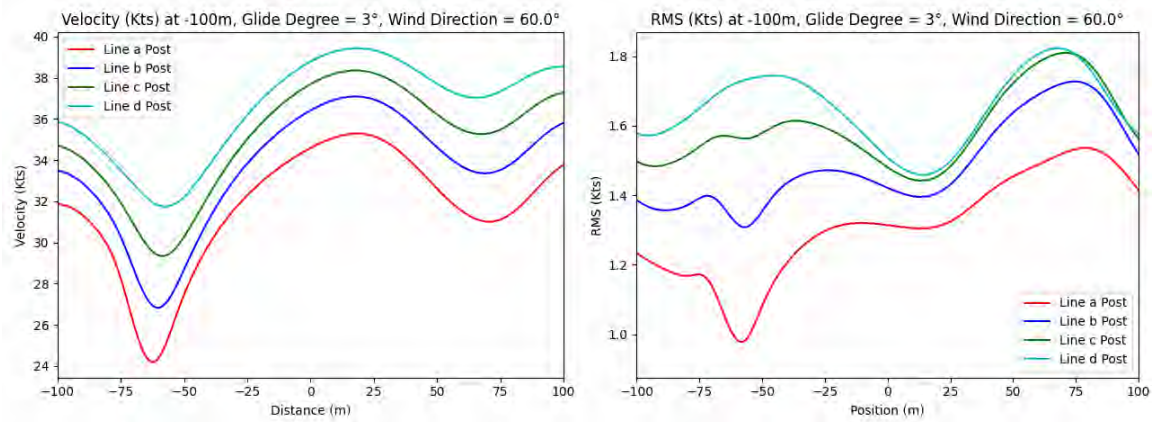


Figure 156: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

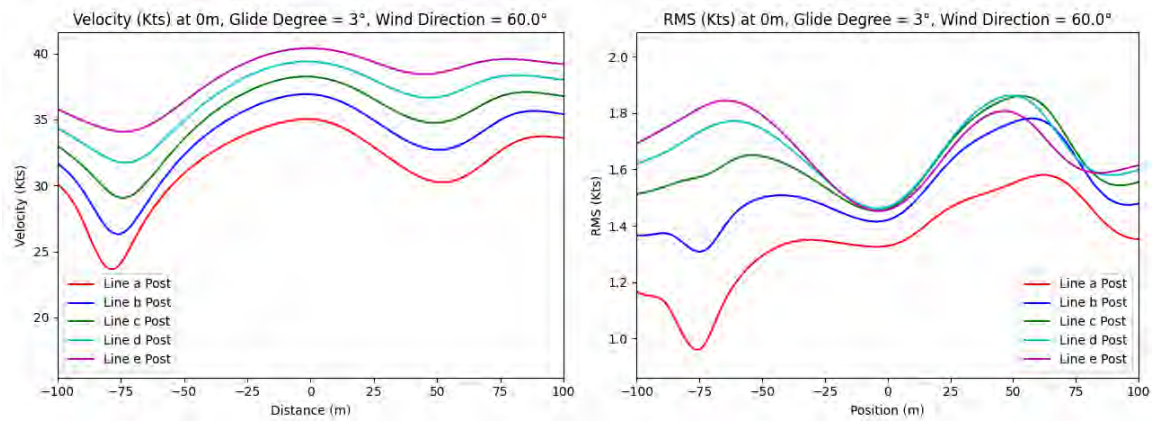


Figure 157: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

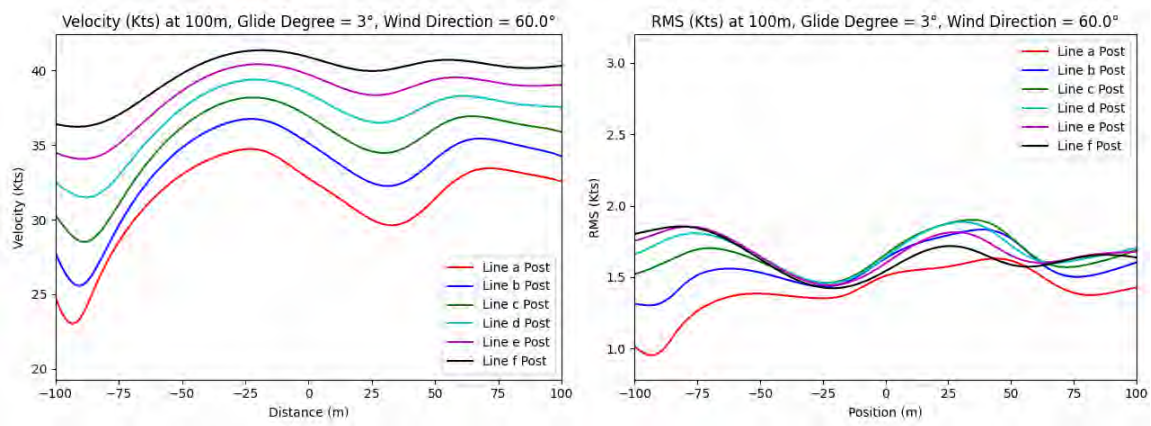


Figure 158: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

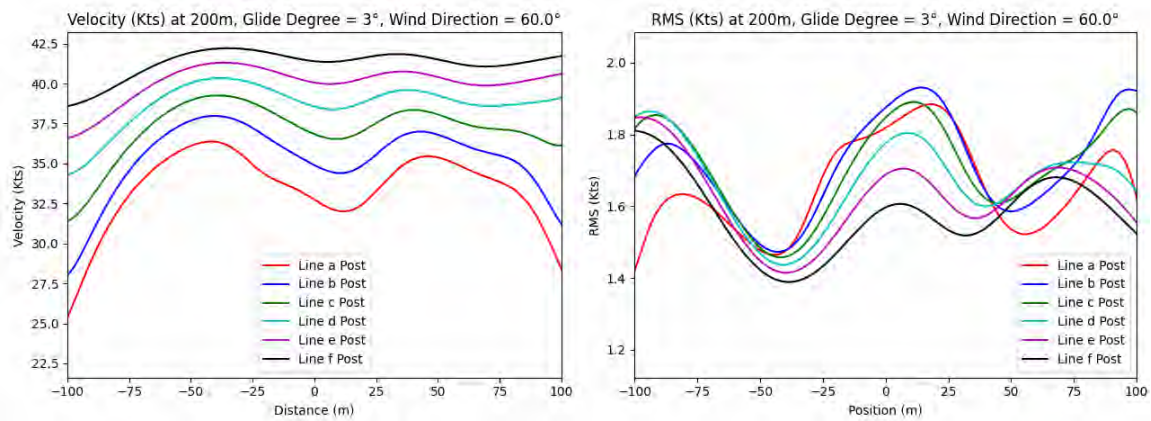


Figure 159: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

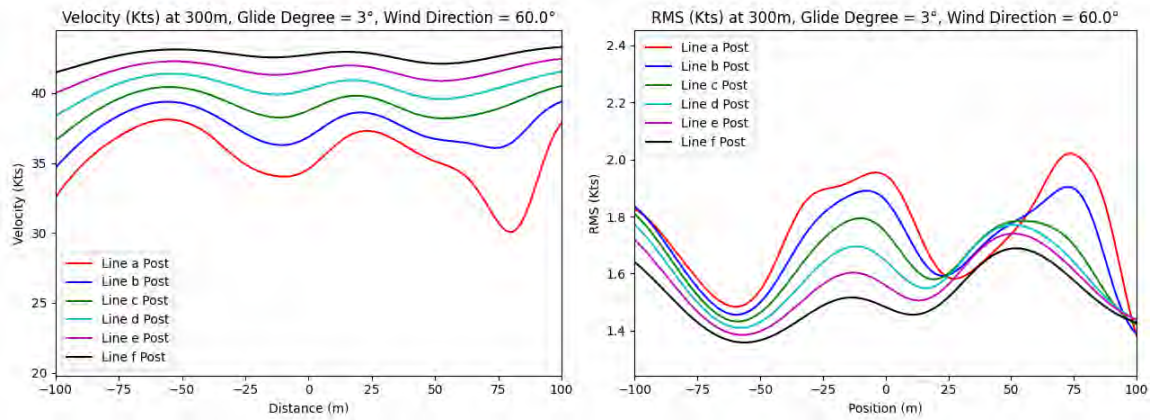


Figure 160: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

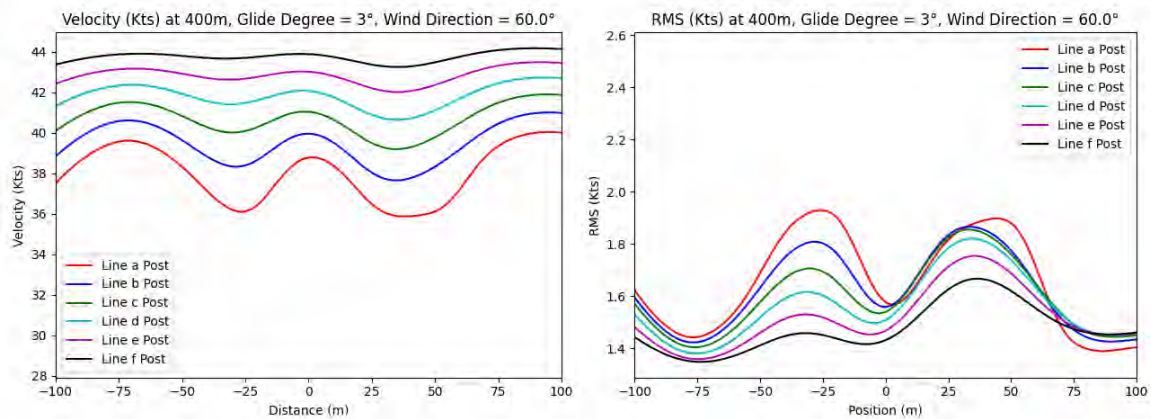


Figure 161: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

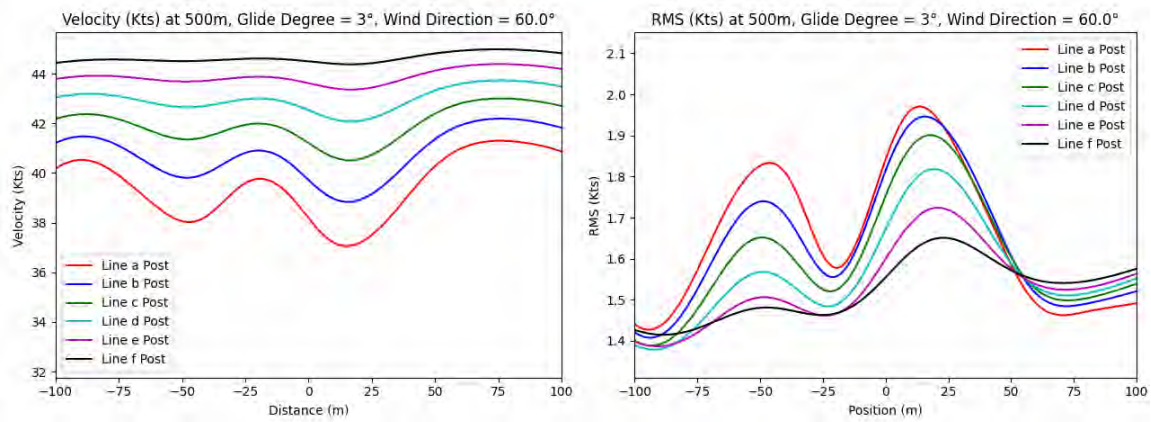


Figure 162: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

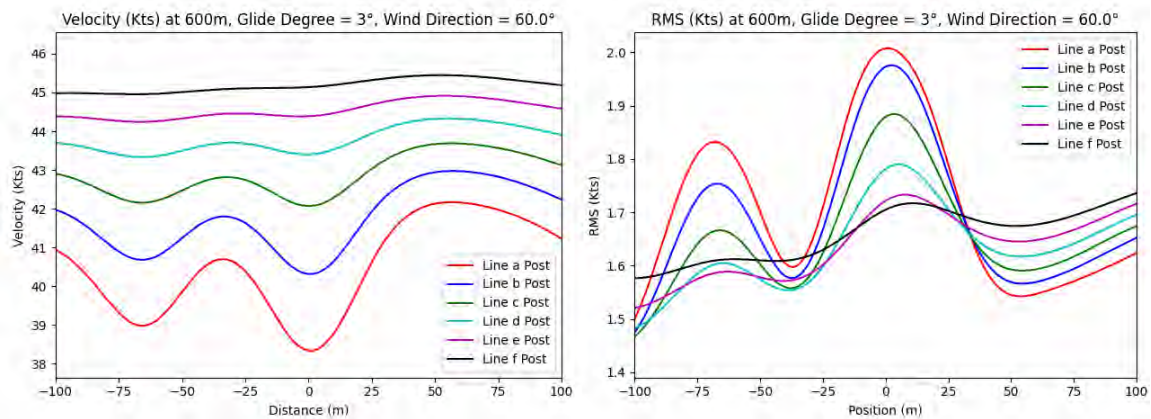


Figure 163: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

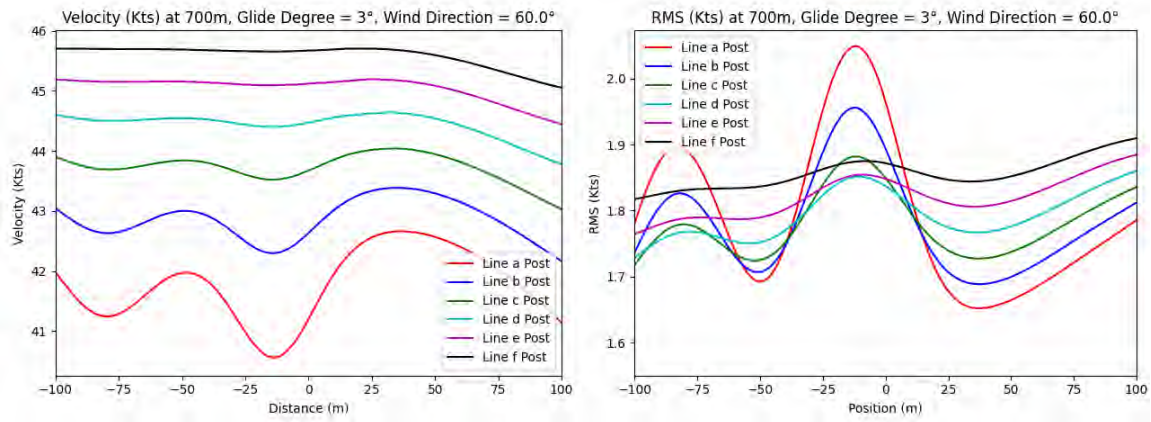


Figure 164: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

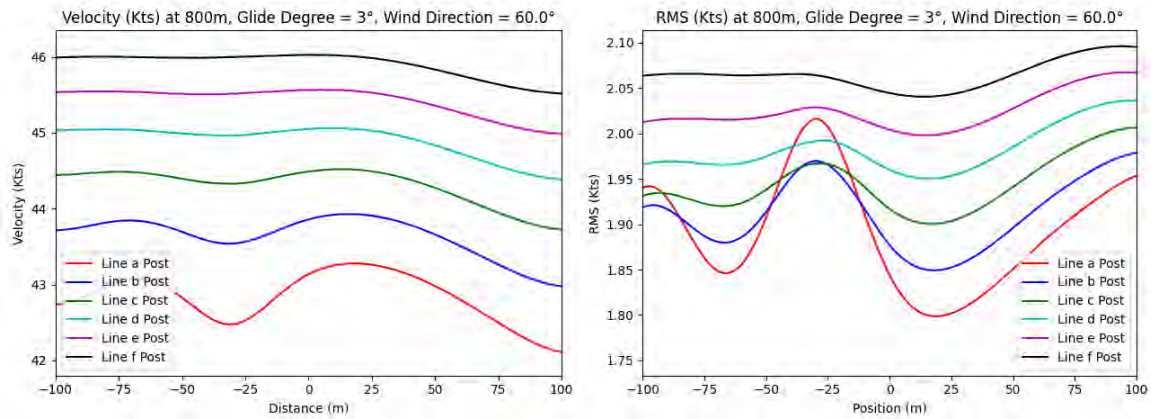


Figure 165: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

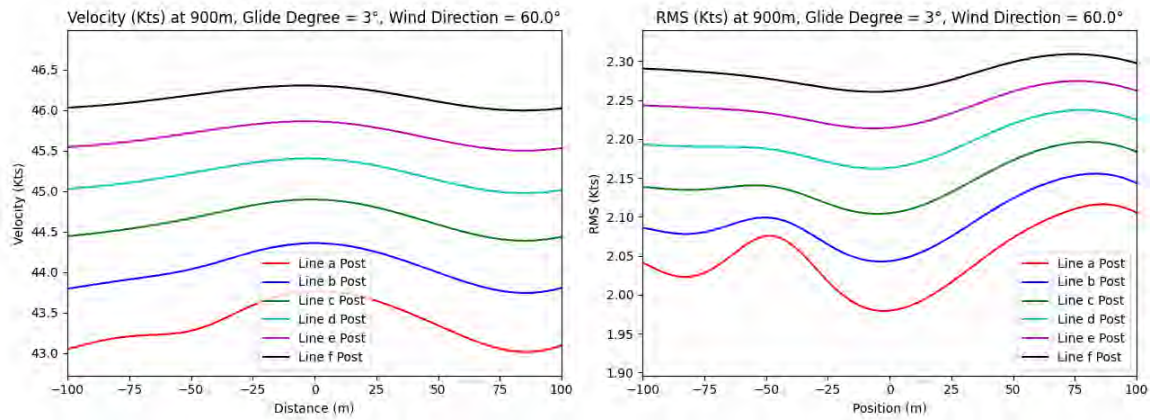


Figure 166: Velocity magnitude (Kts) and RMS (Kts) cross a possible Critical Aircraft Trajectory. Reference wind speed 15 (m/s) - Landing/Takeoff degree 3° - Wind Direction 60°

Velocity magnitude and turbulence deviation values of CFD models along the runway centerline between chainages -500m to 900m, consistent with assessment area according to National Airport Safeguarding Framework (NASF), and up to a height of 60m above ground level for wind direction 60° with 15 m/s approaching speed are shown in tables 17 and 18.

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	43.35	43.47	43.94	44.56	45.05	45.34	45.46	45.5	45.59	45.58	45.53	45.46	45.38	45.32	45.16
55	42.27	42.31	42.9	43.76	44.42	44.75	44.84	44.84	44.94	44.97	44.88	44.79	44.81	44.78	44.64
50	41.17	41.08	41.8	42.9	43.76	44.16	44.21	44.12	44.23	44.31	44.13	43.98	44.13	44.22	44.1
45	39.97	39.72	40.59	41.94	43.02	43.5	43.47	43.24	43.36	43.54	43.22	42.92	43.29	43.58	43.51
40	38.68	38.25	39.31	40.93	42.2	42.75	42.61	42.19	42.34	42.68	42.1	41.48	42.16	42.84	42.86
35	37.35	36.71	38.02	39.9	41.34	41.94	41.65	41	41.18	41.75	40.77	39.71	40.65	41.99	42.13
30	36	35.14	36.75	38.9	40.46	41.09	40.6	39.68	39.89	40.75	39.33	37.79	38.87	40.98	41.32
25	34.65	33.54	35.52	37.89	39.56	40.18	39.47	38.21	38.34	39.69	37.88	35.72	37.09	39.89	40.4
20	33.32	31.94	34.36	36.88	38.59	39.19	38.2	36.53	36.45	38.53	36.39	32.05	35.4	38.79	39.36
15	31.99	30.36	33.29	35.86	37.52	38.08	36.72	34.65	34.2	37.11	34.89	24.72	33.85	37.73	38.19
10	30.58	28.79	32.29	34.75	36.27	36.78	34.97	32.57	31.65	35.06	33.61	18.32	32.47	36.67	36.81
5	28.82	27.08	31.01	33.17	34.47	34.91	32.64	30.15	28.62	31.74	32.03	20.23	31.18	35.34	34.89

Table 17: Wind Speed in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 60°

	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
60	1.5135	1.52968	1.47122	1.36992	1.28798	1.25963	1.27997	1.32194	1.35547	1.41633	1.54962	1.70827	1.85816	1.98292	2.13514
55	1.61128	1.64548	1.57676	1.44356	1.32702	1.28321	1.30533	1.34849	1.3657	1.40695	1.54449	1.70795	1.84061	1.93884	2.07472
50	1.68961	1.74513	1.67364	1.51716	1.36994	1.31101	1.33993	1.39204	1.39406	1.41615	1.56842	1.74213	1.83988	1.89903	2.01484
45	1.74801	1.82303	1.75402	1.58584	1.41604	1.34417	1.38591	1.45695	1.44364	1.44347	1.62346	1.81622	1.86444	1.86373	1.95366
40	1.78028	1.86955	1.80663	1.63822	1.45864	1.37979	1.44108	1.53776	1.51	1.48112	1.6986	1.91553	1.92015	1.83603	1.89306
35	1.78329	1.87892	1.8263	1.66783	1.49141	1.41312	1.49944	1.6242	1.5864	1.5177	1.77219	1.99125	1.99027	1.81715	1.83538
30	1.75638	1.84854	1.8117	1.67332	1.51107	1.44044	1.55543	1.7104	1.67289	1.54458	1.82118	2.00448	2.02661	1.80185	1.78255
25	1.70073	1.77842	1.76233	1.65427	1.51708	1.45967	1.60497	1.79192	1.77367	1.56134	1.83825	1.97281	2.00083	1.7776	1.73501
20	1.61791	1.66963	1.67776	1.60881	1.50719	1.46734	1.64258	1.85511	1.88035	1.58265	1.83053	2.08001	1.91779	1.73133	1.69046
15	1.50723	1.52113	1.55797	1.53469	1.47616	1.45607	1.65659	1.87271	1.95271	1.64272	1.79043	2.17716	1.78305	1.64766	1.64053
10	1.36092	1.32794	1.40018	1.4281	1.41525	1.41418	1.62393	1.80798	1.9322	1.76504	1.69799	1.78773	1.59142	1.51702	1.56652
5	1.15175	1.0721	1.19616	1.27885	1.30793	1.32241	1.49952	1.60195	1.73789	1.81649	1.62049	1.84717	1.30009	1.32283	1.4273

Table 18: Turbulence deviation or RMS in Kts along the runway centerline between chainages -500m to 900m and up to a height of 60m above ground level. Wind Direction 60°

APPENDIX B: VERIFICATION & VALIDATION

It is important to verify and validate the CFD model for numerical studies by comparing the CFD results with experimental data. In this chapter, the CFD model used in the windshear and turbulence analysis is applied on a simplified geometry (a rectangular cylinder with an aspect ratio of 5:1). The flow field determined by the CFD model is then compared with experimental data from BARC (Benchmark on the Aerodynamics of a Rectangular 5:1 Cylinder). BARC addresses the high Reynolds number, external, unsteady flow around a stationary, sharp-edged rectangular cylinder, and the associated aerodynamic actions. BARC provides experimental data of flow field around blocks, which can be used to validate numerical results through comparisons of velocity.

Model Description

Physical Model

In the presented CFD model, the flow within the testing domain is assumed to be incompressible and Newtonian, with temperature and gravity effects neglected. The flow is governed by the Reynolds-averaged Navier–Stokes (RANS) formulation for mass and momentum where the turbulence is modeled using the $k-\omega$ SST turbulence model. The turbulence intensity in this group of study is 30%. The Reynolds number is 112,600.

Model Geometry

The geometry used in this chapter is a rectangular cylinder with an aspect ratio of 5:1, which is shown in Figure 167. Figure 168 shows the sampling location relative to the geometry.

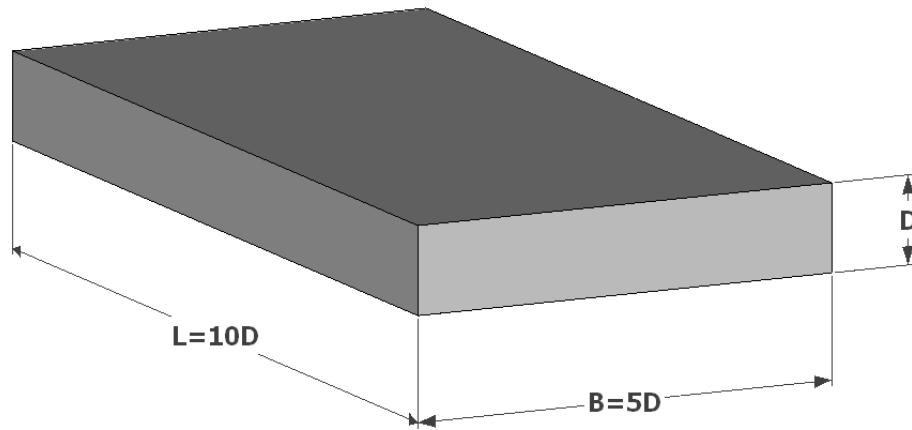


Figure 167: 3D View of the Geometry

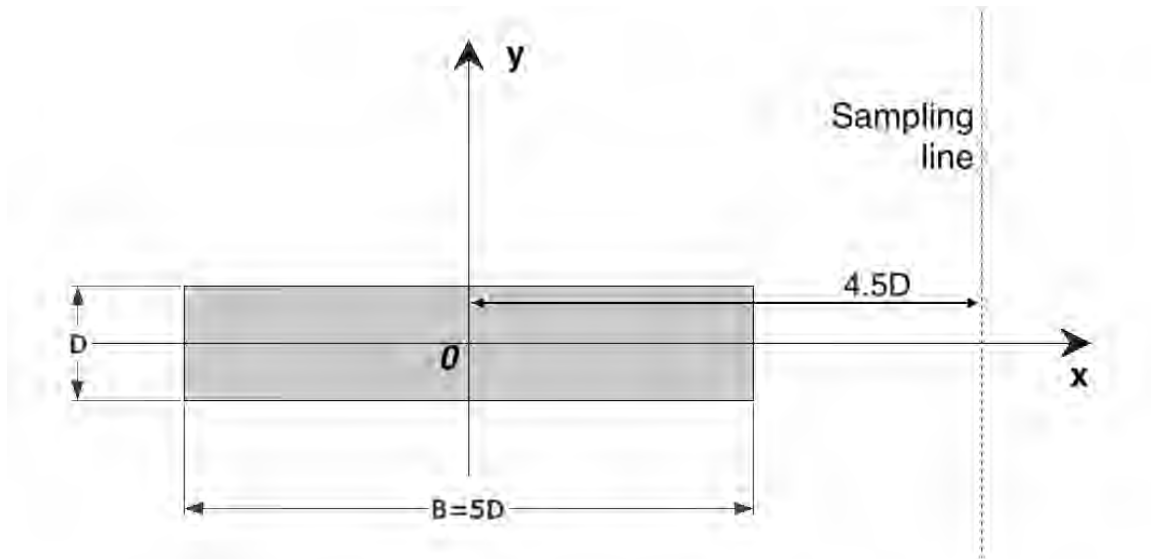


Figure 168: Sampling Location Relative to the Geometry

Computational Mesh

The computational mesh used in the simulations is created using OpenFOAM utilities `snappyHexMesh` and `blockMesh`. It is a hybrid mesh containing a structured background grid and an unstructured hexahedron-dominated mesh in the near-wall region. As shown in Figure 169, the largest cell has a depth of 2m, where the smallest has a depth of 0.0625m. The total cell count is approx. 1.7 million.

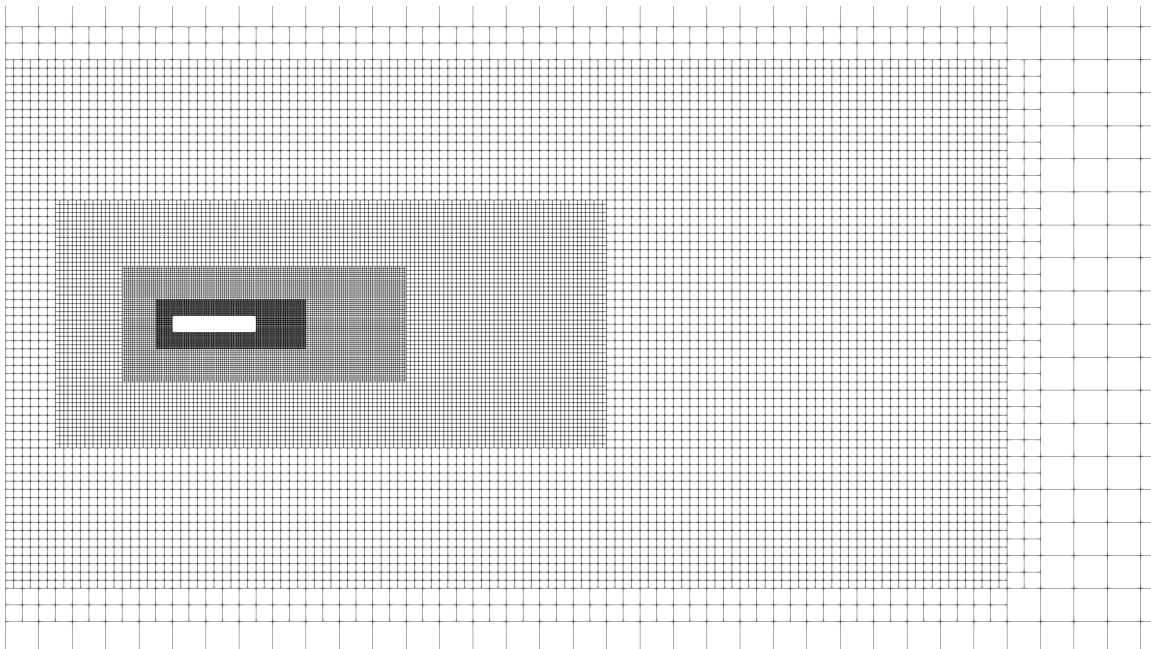


Figure 169: A Cross-Sectional View of the Computational Mesh

Boundary Conditions

Dimensions of the computational domain and the boundary conditions applied on each surfaces are shown in Figure 170.

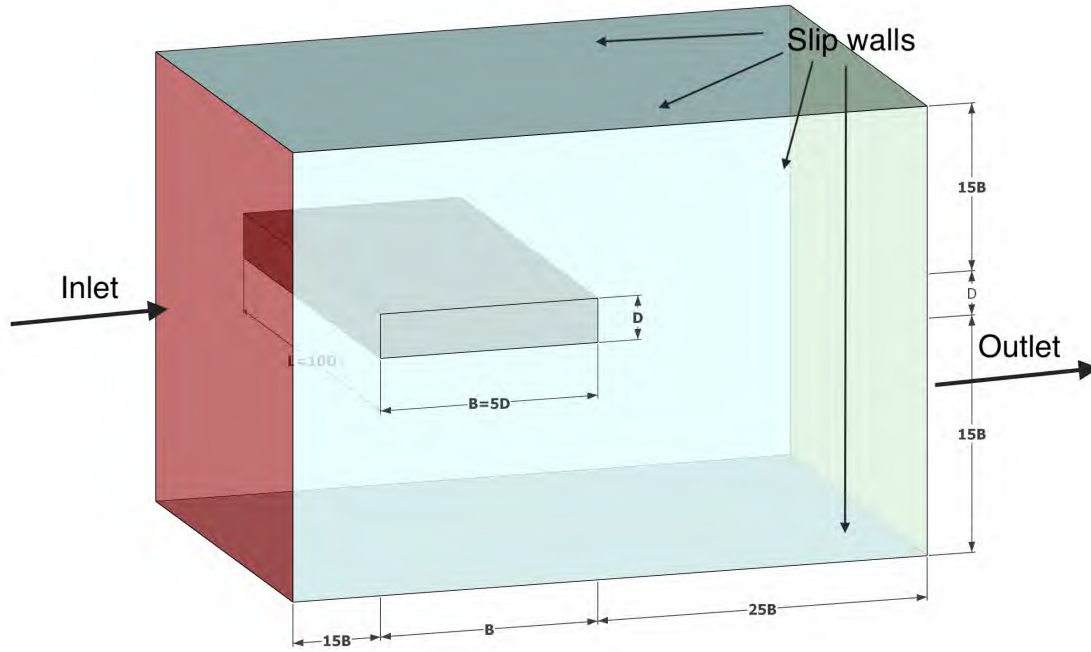


Figure 170: Computational Domain and Boundary Conditions

Numerical Configurations

In this chapter, all simulations employ the PIMPLE algorithm to perform the pressure–velocity coupling (pimpleFoam solver in OpenFOAM-V9). All terms in the RANS equations are discretized using the nominally second-order cell-centred finite volume method, where gradient and Laplacian terms are discretized using Gaussian integration with linear interpolation. Convection/advection terms are discretized using a second-order accurate linear-upwind scheme. The Euler scheme, which is a first-order implicit scheme, is implemented for the time discretization.

Results Validation

Figure 171 shows the velocity field around the cylinder. Figure 172 shows a comparison between the simulation results and the experimental data determined at the sampling location. The velocity results calculated by the presented CFD model agree well with the experimental benchmark data, which indicates that the presented CFD model can provide sufficiently accurate results for the windshear and turbulence analysis.

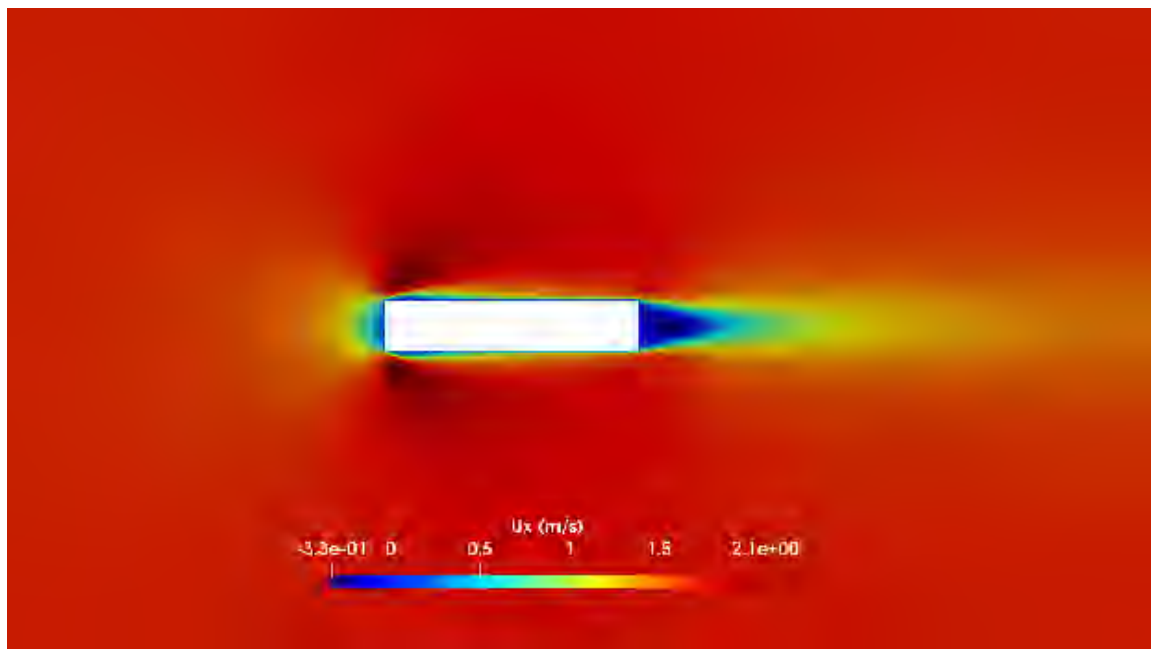


Figure 171: Velocity (m/s) in the x-direction

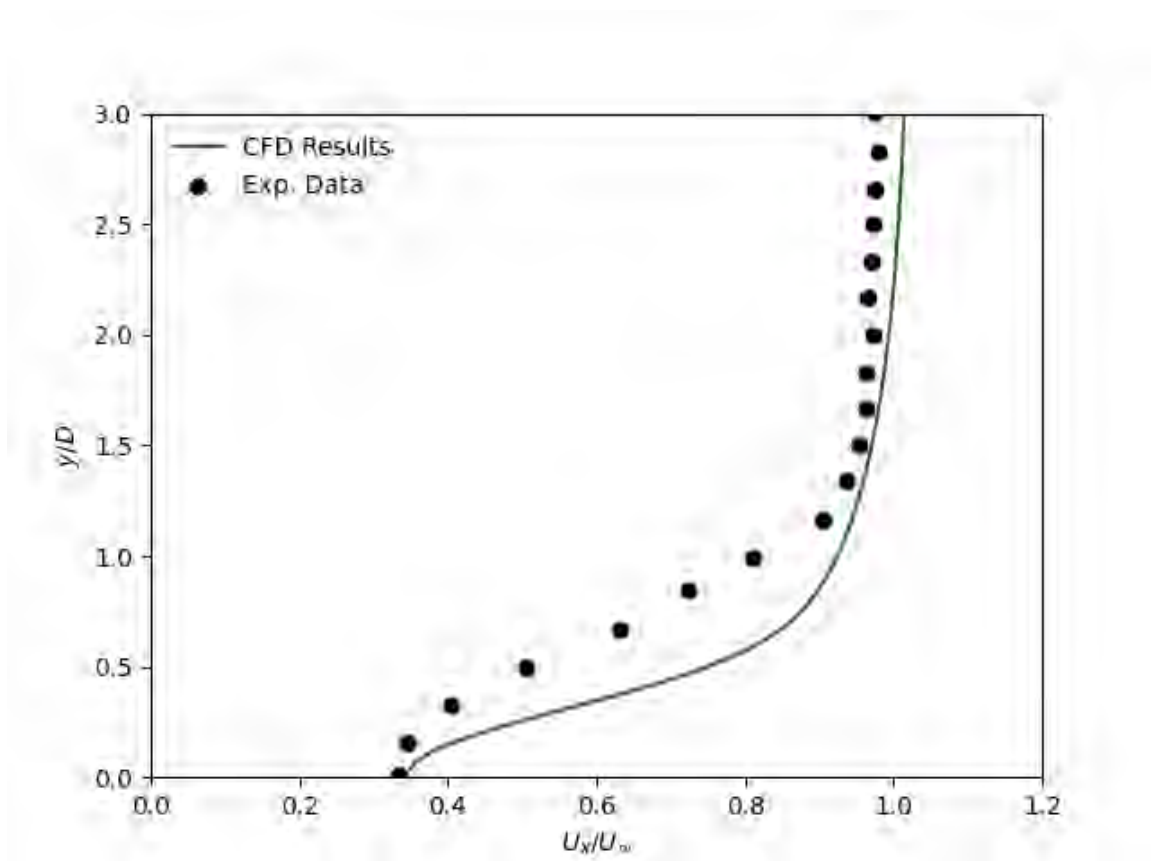


Figure 172: Comparison of velocity in the x-direction at $x/D=4.5$