CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Transportation Sciences
Institute of Air Transport

Problémy s vnímáním během iluze černé díry

Perception Issues during Black Hole Approach

Bachelor Thesis

Study branch: Professional Pilot

Supervisor: doc. Ing. Bc. Vladimír Socha, Ph.D.
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Yiming Su

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Seznam odborné literatury: Newman, David G. An overview of spatial disorientation as a factor in aviation accidents and incidents. Canberra City, A.C.T: Australian Transport Safety Bureau, 2007.

Previc, Fred H., and William R. Ercoline. Spatial disorientation in aviation. Reston, Va: American Institute of Aeronautics and Astronautics, 2004

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Ing. Lenka Hanáková

Datum zadání bakalářské práce: **9. října 2020**

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Datum odevzdání bakalářské práce: **8. srpna 2022**

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V Praze dne .... 2. prosince 2021

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BACHELOR'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Yiming Su

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bachelor's degree – PIL – Professional Pilot

Theme title (in Czech): **Problémy s vnímáním během iluze černé díry**

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Guidelines for elaboration

During the elaboration of the bachelor's thesis follow the outline below:

- The aim of the thesis is to identify the perceptual problems that arise from visual illusion called the blackhole approach.
- Elaborate an current state of the art analysis in the field of blackhole approaches and identify the causes that lead to the wrong adjustment of the approach slope.
- Based on the information from the current state of the art analysis, run an experiment to verify the most likely causes of wrong approach. Perform the experiment using virtual reality with implemented eye-tracking on a representative research sample.
- Evaluate data from each flight and discuss the results.
- Formulate the conclusions of the thesis.

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Graphical work range: according to the instructions of the supervisor

Accompanying report length: minimum of 35 pages of text (including pictures, figures and tabels)

Bibliography:

Newman, David G. An overview of spatial disorientation as a factor in aviation accidents and incidents. Canberra City, A.C.T: Australian Transport Safety Bureau, 2007.

Previc, Fred H., and William R. Ercoline. Spatial disorientation in aviation. Reston, Va: American Institute of Aeronautics and Astronautics, 2004.

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a) date of first anticipated submission of the thesis based on the standard study duration and the recommended study time schedule
b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

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doc. Ing. Jakub Kraus, Ph.D.
head of the Department of Air Transport

doc. Ing. Pavel Hrubeš, Ph.D.
dean of the faculty

I confirm assumption of bachelor's thesis assignment.

Yiming Su
Student's name and signature

Prague .... December 2, 2021

Abstrakt

Vizuální iluze jsou velmi častým potenciálním rizikem pro bezpečnost letu. Mohou způsobit dezorientaci a nakonec vést k nehodě. Iluze černé díry je jednou z vizuálních iluzí, v posledních několika desetiletích již byla příčinou několik nehod, naposledy v roce 2016. Příčina iluze černé díry však stále není jistá. Tato práce se zaměřuje na problematiku percepce při iluzi černé díry během přiblížení, bylo stanoveno několik experimentálních scénářů včetně denního přiblížení, nočního přiblížení bez PAPI a nočního přiblížení s PAPI. K experimentům bylo přizváno 52 účastníků a během experimentů byla zaznamenávána sestupová rovina letadel a pohyb očí účastníků. Výsledky ukazují, že v důsledku iluze černé díry skutečně došlo u účastníků výrazně nízkému přiblížení. Poté při využití PAPI došlo k výraznému zlepšení správnosti sestupové roviny.

Klíčová slova: Letectví, iluze černé díry, let, pilotáž, runway, vizuální iluze

Abstract

Visual illusions are a very common potential hazard to flight safety. It can cause disorientation and eventually lead to an accident. The Black Hole illusion is one of the visual illusions, it has already caused several accidents in the past couple of decades, and the closest one just happened in 2016. However, the cause of the black hole illusion is still not certain. The focus of this thesis is the perception issues of the black hole illusion during the approach, several experimental scenarios were set including the daytime approach, night approach without PAPI and a night approach with PAPI. 52 participants were invited to the experiments, and during the experiments, the aeroplanes' glide path and the participants' eye-tracking data were recorded. The result indicates that the black hole illusions do cause a significant low approach to the participants. Then with the guidance of PAPI, the accuracy of the glide path was significantly improved.

Keywords: Aviation, black hole approach, flight, piloting, runway, visual illusion

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Affidavit

I hereby declare that I have completed this thesis with the topic "Perception Issues during Black Hole Approach" independently, and that I have attached an exhaustive list of citations of the employed sources.

I do not have a compelling reason against the use of the thesis within the meaning of Section 60 of the Act No. 121/2000 Sb., on copyright, rights related to copyright and amending some laws (Copyright Act).

In Prague, 08.08. 2022 ....

Signature

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List of symbols and abbreviations

°	Degree (Angle)
AMSL	Above Mean Sea Level
ATPL	Airline Transport Pilot Licence
CFIT	Controlled Flight Into Terrain
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FSTD	Flight Simulation Training Devices
ft	Feet
GNSS	Global Navigation Satellite Systems
GPWS	Ground Proximity Warning System
ICAO	International Civil Aviation Organization
ILS-DME	Instrument Landing System with Distance Measuring Equipment
IMC	Instrument Meteorological Conditions
IFR	Instrument Flight Rules
LNAV	Lateral Navigation
LPV	Localizer Performance with Vertical Guidance
NM	Nautical Miles
NTSB	National Transportation Safety Board
OLED	Organic Light-Emitting Diode
PAPI	Precision Approach Path Indicator
R-CNN	Region-Based Convolutional Neural Networks
RMSE	Root Mean Square Error
RNAV	Area Navigation
ROI	Regions Of Interest
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VOR	Very High Frequency Omni-directional Range
VR	Virtual Reality
VRFS	Virtual Reality Flight Simulator

Introduction

Flying an aeroplane is a great and complex thing, and after a century of development in the aviation industry, commercial aviation is now widely regarded as the safest means of transport in the world. However, despite this, accidents caused by human factors are still a major part of air accidents, and much of this is due to the weakness of human perception.

Unlike most birds, which have well-developed attitudes and directional perception systems, human beings' perception systems can only provide some basic acceleration perception to maintain balance when walking or running. In-flight, the majority of manoeuvre aeroplanes are based on visual signals, although today's aircraft have advanced instrumentation and fully automatic piloting to assist humans during flight. But some limiting factors can still exist in extreme conditions, such as night flying or bad weather, etc. At the same time, human piloting ability is also limited by other factors such as cumbersome procedures that increase the workload, fatigue after long flights, etc. All of these factors increase human misjudgement of the perception system and lead to incorrect handling of the aircraft. In addition, visual illusions are also a component of aviation safety. In particular, non-precision approaches in poor visibility, bad weather or at night can lead to Controlled Flight into Terrain, which means that pilots may not be able to recognize the hazard until it is too late.

The term "Black Hole" approach described a certain condition of the illusion that occurs in featureless terrain during an approach to landing. For example, landing on water or dark terrain can cause the pilot feels the aeroplane is at a higher height than it actually is. Pilots who do not recognise this illusion will make a lower approach. This may not seem like a problem, but if there is an obstacle under the glide path, an accident then could exist.

Since the term “Black Hole” illusion first written into a National Transportation Safety Board (NTSB) accident report in the 1970s [1], many initiatives have been established to try to avoid the effects of this illusion on aviation safety. The first initiative was the Boeing team's design of a night vision approach simulator that could vary the intensity of illumination to assist in training pilots to fly in the night visually [2]. Subsequent research has led to the introduction of the Visual Approach Slope Indicator (VASI) to assist pilots in following a standard approach glideslope. The VASI has now been replaced by the Precision Approach Path Indicator (PAPI) in accordance with ICAO Annex 14: Aerodromes [3].

In summary, the area of interest of this thesis is the perception issues of "Black Hole" illusions during the approach phase of flight. Due to human physiology and the position of the eye, visual illusions cannot be completely avoided, even experienced pilots still perceive visual illusions. All pilots are therefore taught to trust the instructions from the flight instruments over their own perceptions in all situations, otherwise, the safety of the flight can be compromised. Therefore, this thesis sets out to build a flight simulator by using a VR headset and a flight control simulator system to create an ideal Black Hole illusion environment to verify the affections of the Black Hole illusion during the approach phase of flight. An attempt is made to analyse the experimental flight data and the eye tracking data recorded during the flight in order to demonstrate the perception issues of the Black Hole illusion during the approach.

1. Current state of the art analyses

The following chapter is the approach to further developing the topic by providing information regarding theories of perception and the black hole illusion.

1.1 Overview of the visual illusions

Visual illusions occur when the pilot's eyes made a faulty assessment of the aeroplane' s orientation or position in relation to the reality. A Flight Safety Foundation analysis in 1999 determined that 21% out of 76 incidents and accidents were caused by flight crew disorientation or visual illusions from the final approach or landing, and 59% of the accidents or incidents were caused by a circumstantial factor of poor visibility [2].

Flying visually is the first lesson for every pilot, so finding a reliable visual reference is a critical part of the flight. However, human being's eyes are not suitable for high-speed movement in the air. The light signal could go through eyes and then present on the retina and the retina then exchange the light signal into the biological signal and transform it into brain. Theoretically, everything could be seen is an image from brain, and when the condition is very harsh brain could make mistakes, which is the Optical illusion. For example, the Blackhole illusion is one of the optical illusions [2].

Flying an aircraft is a difficult job combining a lot of things, many of them could put lives in danger. For flying, the most important part would be how to fly with knowing its own particular attitude or in other words don't get disorientation. The reason why it is so important is that flying in the sky means the movement are in three-axis but all information that can be perceived by the eyes is a result of the light-sensitive cells captures the images thus they are in 2D [4]. However, the two eyes human beings have are located in different positions and they see objects from a different angle. By receiving those visual signals, the brain could only tend to subjectivity the complete images from only partial visual signals [4]. By flying visually, maintaining visual reference insight is one of the most important parts of the aircraft manoeuvring. Visual illusions are the consequences of the absence of a visual reference, which provides the pilots with the perception of the aeroplane' s position or orientation. In case of loss, the pilot can fall into spatial disorientation, this situation demonstrates the inability of a pilot to correctly recognize the aeroplane' s airspeed, altitude or attitude in accordance with the ground reference and eventually lead to the accident. By knowing the current position properly is the only way to adjust aircraft. And that's the reason why in the first Instrument Flight Rules (IFR) class, every pilot has been told that always trust their instruments instead of their perception [5]. Once pilots lose the visual contact to the ground references, the pilots could suddenly lose their idea of adjusting aircraft manoeuvring [5]. So, when flying at a low altitude during the Visual Flight Rules (VFR), for example, the pilot must be able to accurately perceive and interpret the environment. However, due to the biological limit, the human body is not good at dealing with the relatively quick movement during extreme that could occur in aviation [5]. Therefore, brain could misinterpret sensed images, and in certain conditions, it could cause accidents.

However, the visual illusions do not affect only the spatial disorientation. It can also be caused by environmental changes. For example, the False Visual Reference could make the pilot miss orient the aeroplane in relation to the false horizon [6]. This can happen when flying to a banked cloud, flying towards the overcast cloud, night flying over the dark terrain with the ground illumination indistinguishable from the stars or flying over a starless sky with the ground illumination clearly defined into horizons [6], such as exemplified in Figure 1.

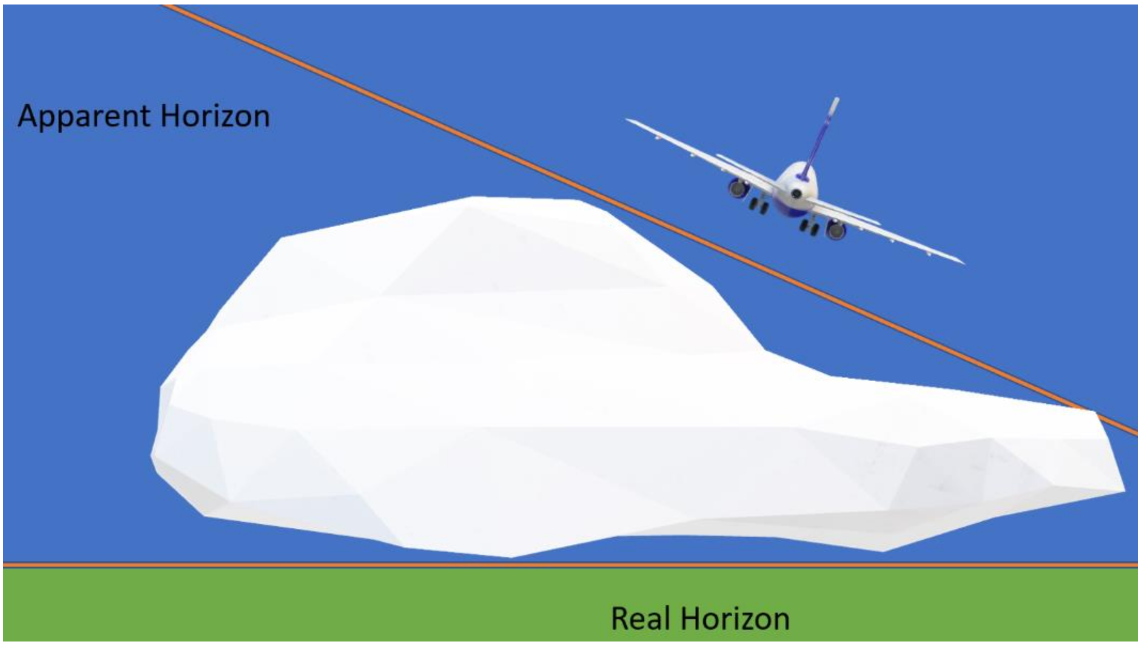

Figure 1: Illusion of false horizon

The Aerial Perspective Illusions could make pilots fly a different slope of their final approach. This illusion defines the specific condition of diverting from the glideslope vertically caused by the different widths, up or down sloping runways, and upsloping or down sloping the final approach course as the consequences. The pilot learns to recognize the normal glide path by developing and recalling a mental image of the expected relationship between the length and the width of an average runway [6]. Such as exemplified in Figure 2.

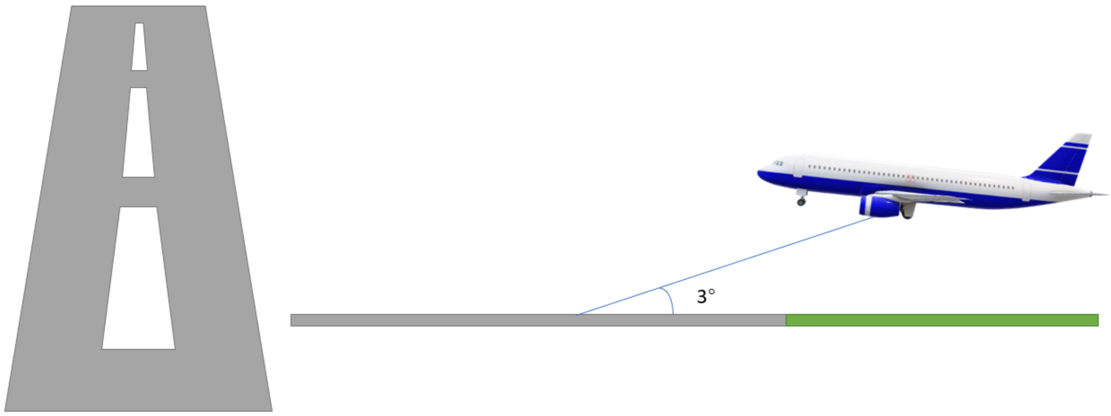

Figure 2: Standard glideslope

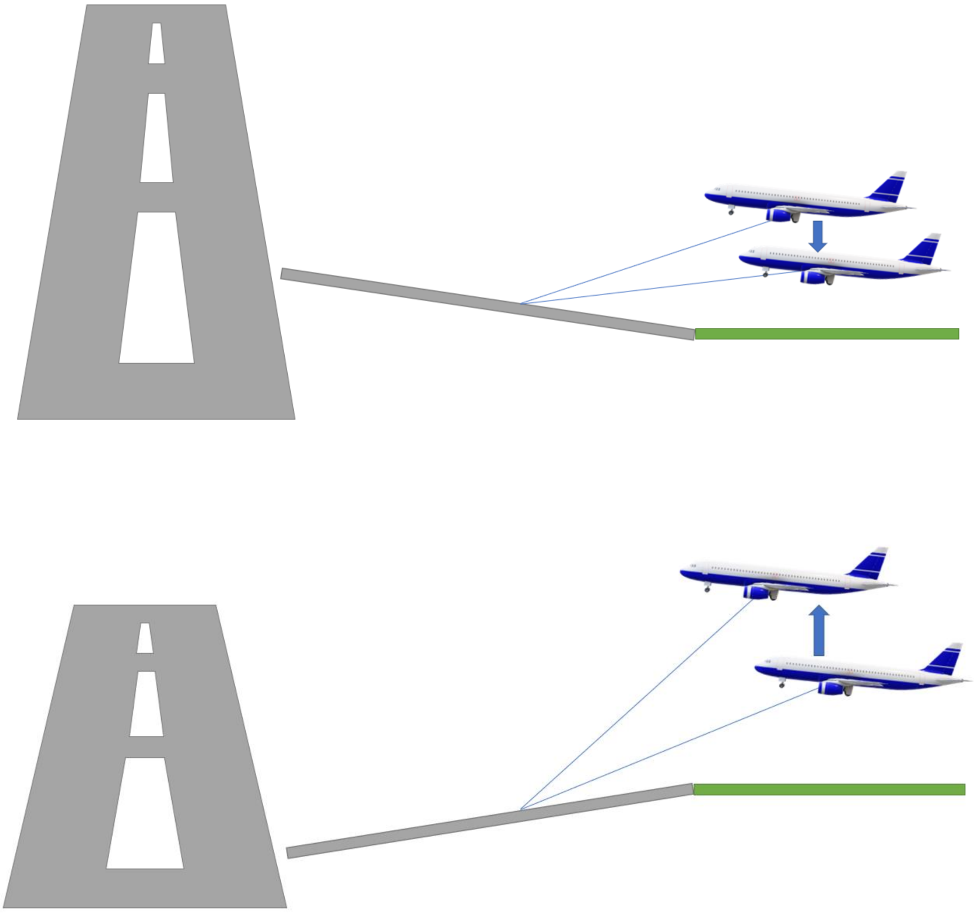

Figure 3: Wrong glide path due to runway slope

A final approach to an upslope runway would produce a visual illusion of flying above the normal glideslope and it can turn out with a lower-than-normal approach path, which, could lead to an accident if the aeroplane is too close to the runway. And a final approach to a downslope runway would inversely produce a visual illusion of flying lower than the normal glideslope and it can cause a higher-than-normal approach path, which, could lead to a go-around or overshoot the runway if the pilot intends to land [6] (See Figure 3).

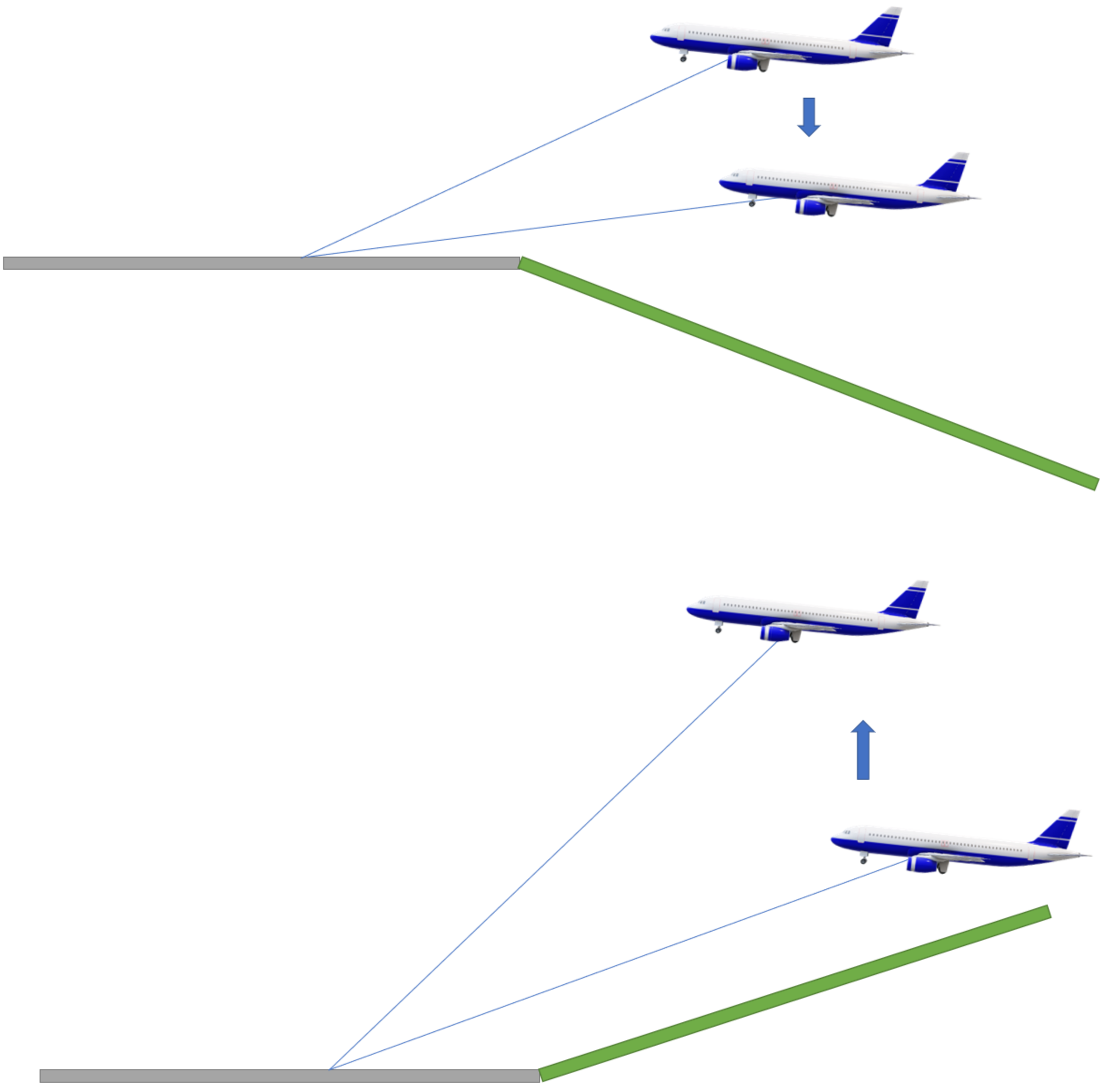

Figure 4: Wrong glide path due to sloped terrain

A final approach to an upslope terrain in the front of the runway would produce a visual illusion of flying below the normal glideslope and it can turn out with a lower-than-normal approach path, which, could lead to an accident if the aeroplane is too close to the runway. And a final approach to a downslope terrain in the front of the runway would inversely produce a visual illusion of flying higher than the normal glideslope and it can cause a higher-than-normal approach path, which, could lead to a go-around or overshoot the runway if the pilot intends to land [6]. Such as exemplified in Figure 4.

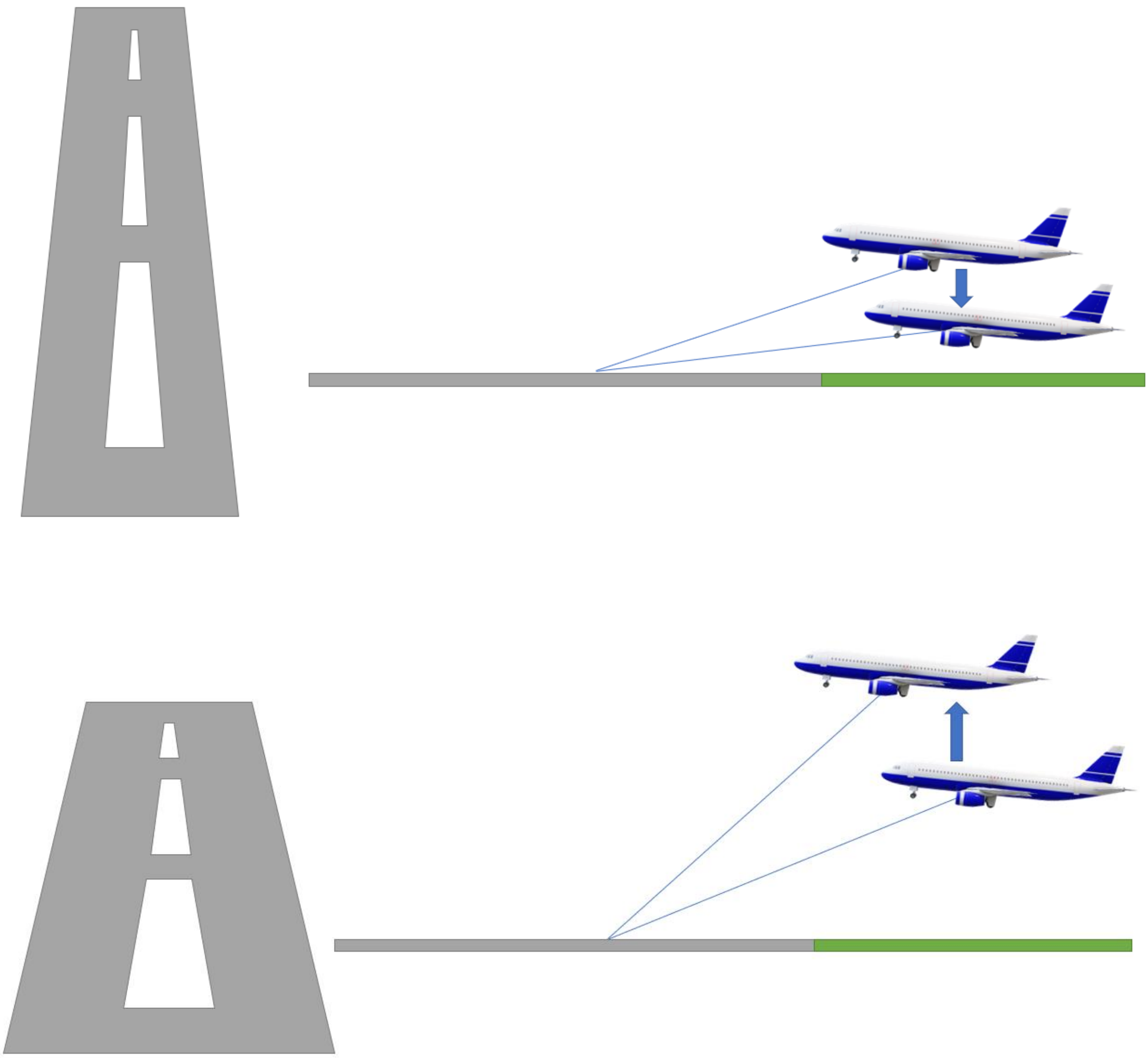

Figure 5: Wrong glide path due to change of runway size

A final approach to a narrower than usual runway would produce a visual illusion of flying above the normal glideslope and it can turn out with a lower-than-normal approach path, which, could lead to an accident if the aeroplane is too close to the runway. And a final approach to a wider than runway would inversely produce a visual illusion of flying higher than the normal glideslope and it can cause a higher-than-normal approach path, which, could lead to a go-around or overshoot of the runway if the pilot intends to land [6], Such as exemplified in Figure 5.

These basic runway illusions all could lead to a final approach fly higher or below the defined glideslope. Whereas the hypothesis would come up with the same condition could also lead to the same result even with the black hole conditions.

1.1.1 Methods for the Reduction of visual illusions

Even though, there are several instruments including Instrument Landing Systems, GNSS LNAV, RNAV, etc. could help the pilot to find the correct glideslope. However, the Precision Approach Path Indicator (PAPI) is more common to being used in the visual approach, primarily assisting by providing visual glide slope guidance in the non-precision approaches environment. It is a combination of 4 lighting units which could provide the specific colours of light with a defined angle. Such as exemplified in Figure 6.

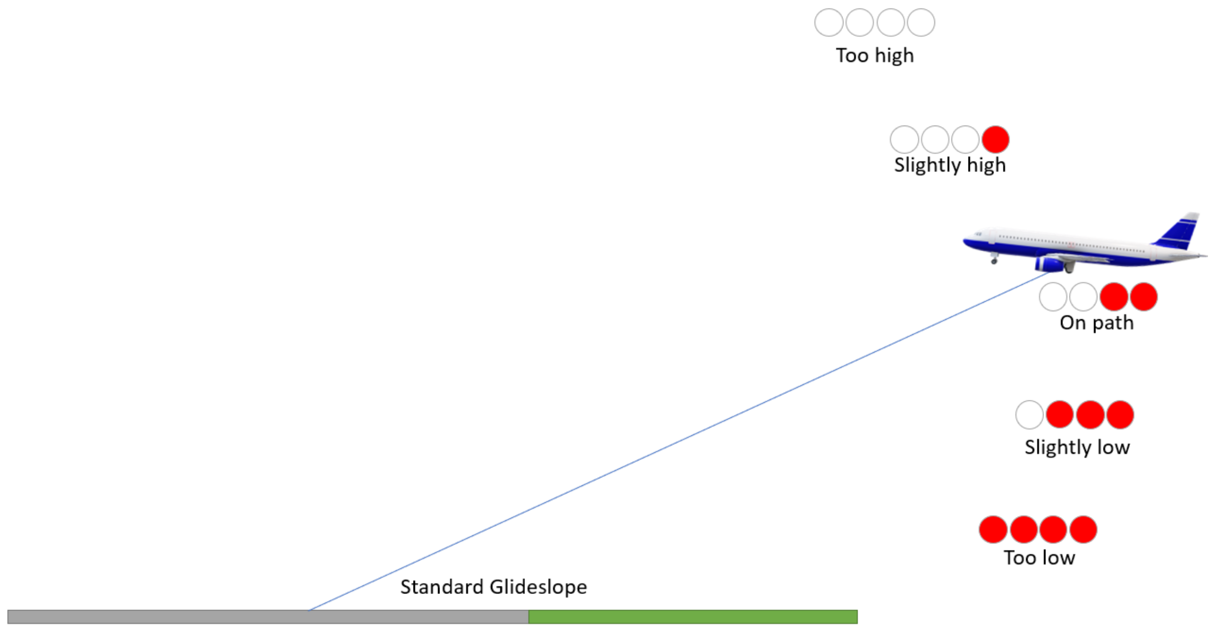

Figure 6: Functionality of a PAPI visual aids

When the aeroplane flies just on the glide path, it will indicate 2 red lights and 2 white lights. When an aeroplane flies higher than the defined glideslope the PAPI will indicate more white light instead of red light. When it will be lower than the defined glideslope, it will indicate more red light instead of white light [7]. According to the advice of the Federal Aviation Administration (FAA)'s Aeronautical Information Manual that the lights of the precision approach path indicator should be able to visualize from 5 miles during the daytime and up to 20 miles at night time [7].

The visual path guidance of the PAPI is typically designed to provide the safety obstacle clearance for plus or minus 10 degrees horizontally of the extended runway centre line and down to 3.4 NM from the runway threshold [7]. So that a descent using the guidance of PAPI should not be used before the aeroplane is fully aligned with the runway. If the pilot could fly the aeroplane strongly following the indication from PAPI, theoretically the influence of the visual illusions should be able minimized.

1.2 The Black hole illusions

1.2.1 General cause of the black hole illusions

The term "black hole approach" described a certain condition of the illusion that occurs in featureless terrain during an approach to landing. It's been founded on a study that described the importance of features in the visual field and the critical role of the ground plane for visual reference. At the beginning of the research when the word "black hole" illusion was invented in the 1950s [8], the researchers thought that the black hole illusion does not belong to the runway illusions category, because their research only described the obstacles in the front of the runway. They found that the situation during the night over the lake or with a vast area of standing water or across unilluminated terrain the runway is the only part that has been illuminated.

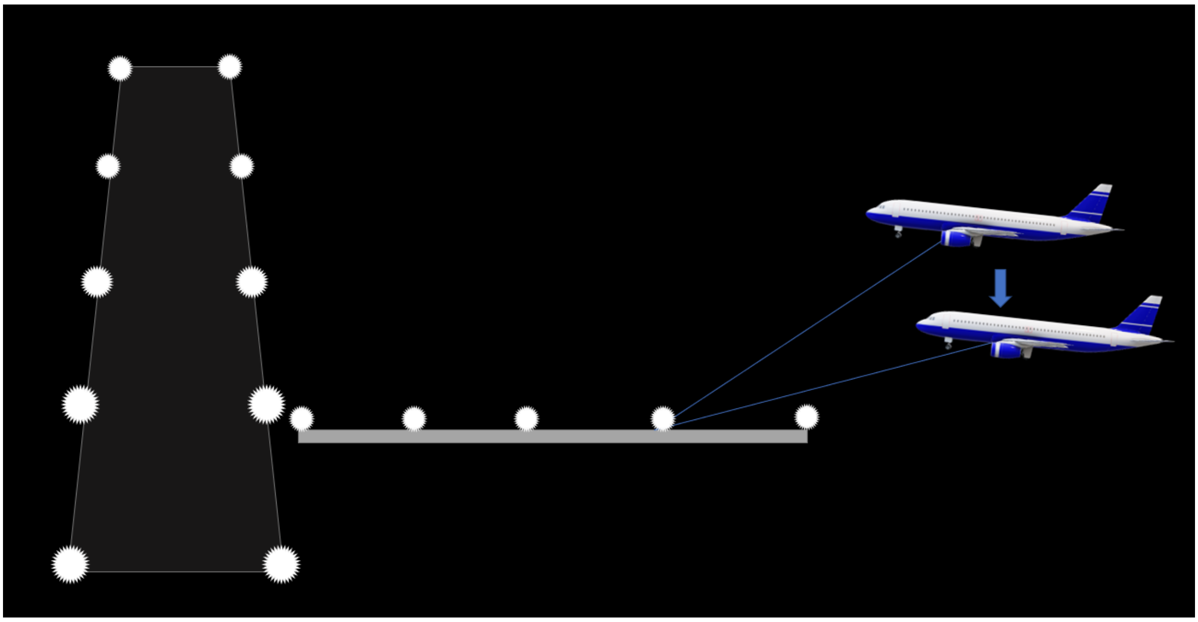

Figure 7: Black hole illusion due to runway lights

The light of the runway has its own heights which is the particular reason for circumstances that make the pilots feel that he's closer to the runway than he really is and due to the other terrain being in total darkness so the pilot lost their perception of depths. So that instead of flying on the glideslope, they can turn to decent more and try to catch the glideslope according to the light source, which an approach with a lower than usual glideslope can be made as a consequent (See Figure 7) [8]. And then they put the black hole illusion into the categories as one of the optical illusions [8].

After analysing 4 accidents, another research in the 1970s points out something different [9]. When pilots fly an aircraft on the final approach underneath the overcast cloud during a dark night pilots could only recognize the illuminated ground (runway light, street light, etc.) and the runway. The place without being illuminated would be total darkness. And when pilots tried to do the visual approach to the runway, they would try to maintain a constant angle of the runway view [9]. Such as exemplified in Figure 8.

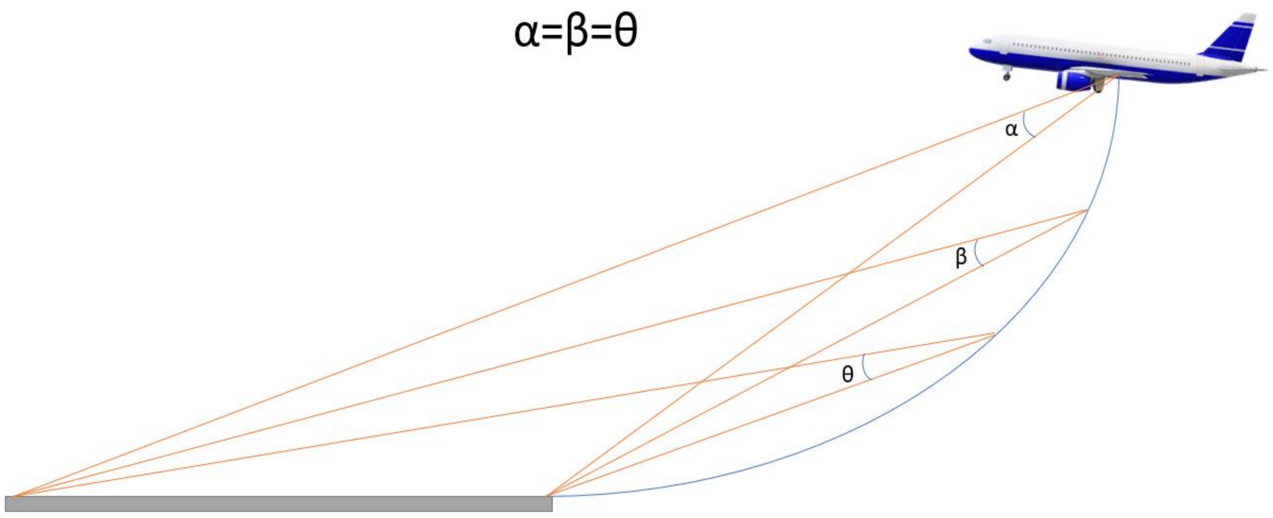

Figure 8: Black hole approach schematic

When flying an arc like this, the final approach course can be lower than the defined glideslope. Research from 1990 found that when the final approach is long enough the pilot may not even notice that they are actually lower than the glideslope [10]. And it also points out that the cause can be associated with the runway illuminations, a bright illuminated runway could make the pilots feel close to the runway, which can turn out an earlier than normal descending. In their experiments, by turning the runway light dim their pilot performs a shallower approach and vice versa. They proved their point through several experiments; however, the experiments have not been done with the black hole conditions [10]. The same research also points out that their experiments proved the light of the city or a rising terrain beyond the runway can also affect the approach glide path. Both rising terrain and the light of the city could provide pilots such an illusion that they are higher than they really are, and makes them fly lower for the corrections. See Figure 9.

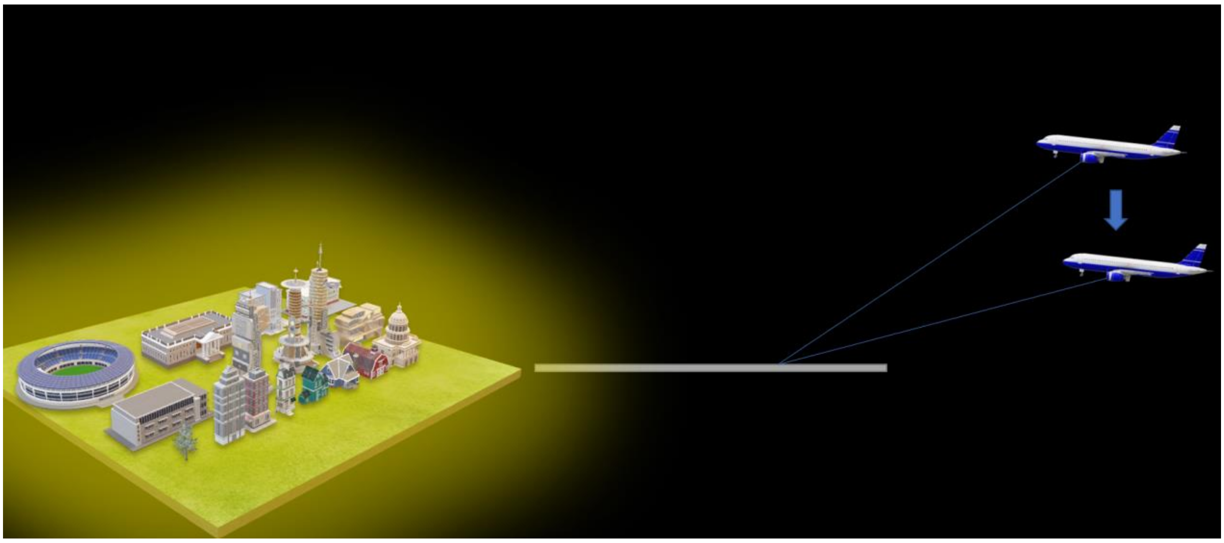

Figure 9: Black hole illusions due to light beyond the runway

Whereas Another research points out that the cause can be due to the lack of illumination, pilots lost their definition of the altitude and mistakenly feels that they are higher than they really are. So, they turn to descend more to catch the ideal position from their own mind which creates the consequence of a lower approach [10].

1.2.2 The black hole illusions analysis

According to a survey of 141 experienced pilots, 79% of them underwent this illusion [11], which means this could be a common problem that happens all the time. Thus, even though that visual approach is almost the first type of approach that student pilots learn, but it is therefore very important that pilots effectively monitor the instruments to ensure that every single data relative to flying is according to the normal approach procedures. A survey in 2008 found that the diversion from the glideslope caused by the black hole illusion happened most in the distance from 0.9 km to 8.3 km on the approach to a long and narrow runway [12].

Whereas, the fresh pilot had a more stable performance compared to the one with more experience [12].

In the research of Naval Aeromedical Research Lab in 2020 believes, the effect of the black hole illusion was more pronounced for longer runways and lower altitude starts than for higher altitude starts [13]. Also, the distance at night could be significantly underestimated and the distance during the daylight is overestimated. Thus, a comparison of day and night approach angles showed that the aircraft tended to fly above the 3° glideslope during the day and below it at night, but the difference around the glideslope was similar [13]. The glide path could also be affected by the slope and the wideness of the runway itself compare to the runway that the pilot is familiar with. Due to the illusions, pilots feel the aeroplane is higher than it should be and manoeuvring it to fly lower. As long as the aircraft is close to the runway, this illusion can be fixed, and pilots would be able to fly back to the glideslope. Thus, by the illusion, the real glide path would be presented as a curve which banking to the ground. If there are any unilluminated obstacles that occur below the glide path, then a potential hazard could result that the curve glide slope could lead the aircraft to fly below the obstacles and cause the accident [13].

However, some others another research believes that it is because that the distance during the night comparing the daytime could be always underestimated [14]. Because the illuminations on the terrain could play a very big deal in the effects on the glideslope curve and it is the cause of the accuracy distance judgement affected by the illumination to the terrain. So, by underestimating the distance, the pilot would descent more to catch the wrong glide slope which creates by the wrong judgement of the runway distance. And by close to the runway, they could realize that it is lower than they are supposed to and correct the aeroplane by reducing the descending rate, and that caused the curve on the glideslope [14].

1.2.3 Major accident of black hole illusions

One of the most infamous cases of black hole illusions during approach would be the accident of Pan Am Flight 806 at Pago Pago International Airport on January 30, 1974, which also known as the first case of the term "black hole illusion" ever being written into the official accident report. The accident involved a Boeing 707-321B, which was on the final approach to Pago Pago Airport. The visibility at the moment was significantly reduced due to heavy rain over the airport and also lots of wind shear has been created as well [1].

During the final approach of the flight, the flight crew successfully catch the ILS-DME from runway 05 on the captain's side, however, the navigation receiver selector on the co-pilot side was still remaining in the VOR position. By continuing approach to the heavy rain, the aircraft soon suffered from the strong wind shear and rain drag. The flight crew tried to fight against the unstable air and maintain the stability of the aircraft. But the weather was too poor so they failed to hold the aeroplane stable. And after a suddenly climb with wind shear, the crew pushed the nose down and then they seem fallen into the black hole illusions and never pull the aeroplane back until they crashed into the terrain [1] (See figure 10).

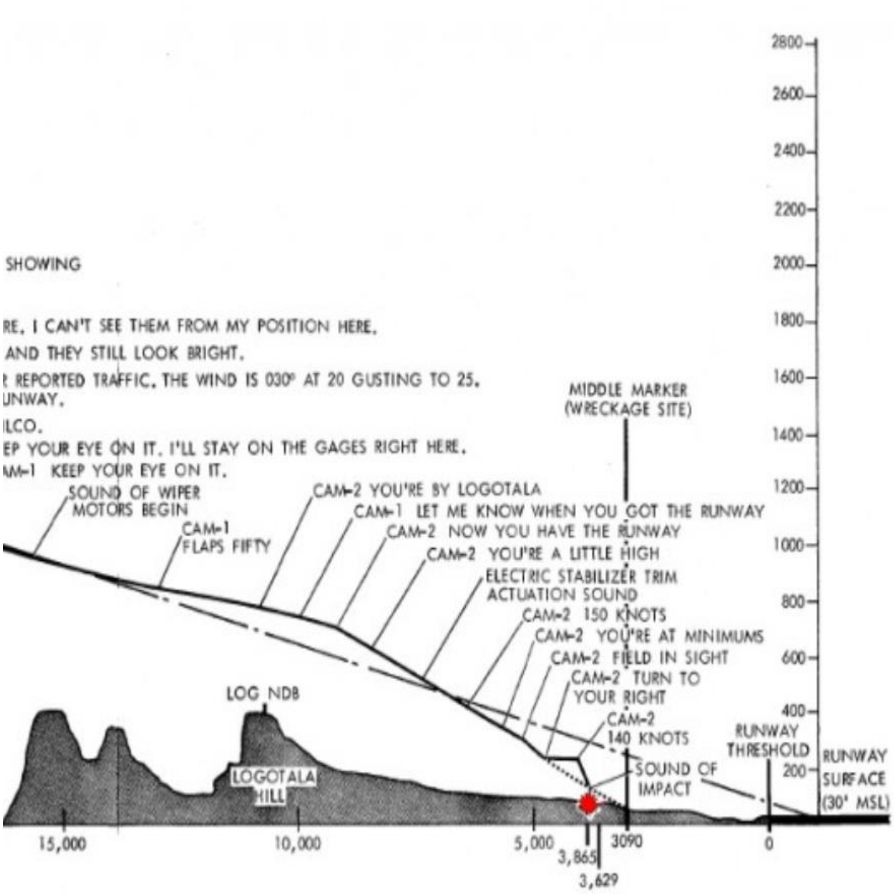

Figure 10: Glide path of Pan Am flight 806 [15]

The final report of the accident points out that due to the heavy rain above the airport, many of the wind shears were crated near the runway and the visibility was rapidly decreased in some of the phases at the final approach course. It makes the flight crew could visualize the runway and the visual approach slope indicator (VASI) intermittently only [1]. After the co-pilot called out that they have both runway and VASI in site, they can still loss them during the approach. The main factor of the accident may be the flight crew's late recognition and failure to correct the sudden changes from the poor weather in a timely manner. So, an extremely high descent rate across the wind shear was made as the consequence. Due to the poor visibility at the final moment, the captain instead of flying according to his instrument he tried to watch out of the windscreen and look for the runway and seems falling into the black hole illusions so he allowed the aeroplane to descend without any corrections. The flight crew was not operating following the standard operating procedures can be another lead to the accident as well. The co-pilot neither selected his instrument for the ILS-DME mode but remains on the VOR mode which makes him fail to recognize that they were too low from the glideslope provided by the ILS instrument nor report the vertical speed from the vertical speed indicator where it was a clearly indication that they were descending with an extremely higher speed before they crashed. And also, the captain failed on doing his cross-check properly before the initial phase of the final approach which he may be able to analyse those missing parts from his co-pilot and asked him to correct them [1].

As another example to demonstrate how the black hole effect approaches, the FedEx Express Flight 1478 with the registered number N497FE should be used. It was one of the most typical accidents describing how the black hole illusions affected flight safety. The flight involved a Boeing 727-232F, which was on the final approach of Tallahassee International Airport runway 09 over the unilluminated terrain within the night visual conditions [16].

During the final approach of the flight, the captain established the final track of runway 09. Around 2 1/2 miles to the runway threshold the PAPI indicated 3 red with 1 white, however, the captain was a colour blind so he couldn't read from the PAPI lights, therefore his kept his decent rates and soon the PAPI indicated 4 red signals which according to the standard operating procedures of the airlines, a go-around should be initiated. However, neither the first officer nor the flight engineer was noticing their captain about the situation, whereas their caption was not able to read the PAPI at all. After a few whiles, the ground proximity warning system (GPWS) sounds "five hundred", which tells that they were 500 ft above ground. The captain responds with "stable". And at this moment the first officer says that they need to be higher or they may lose the runway. But the captain was still descending and stated "disappear...a little. Think we'll be alright." Soon later they impacted 50-foot (15 m)-high trees which were around 1100m before the runway threshold and crashed into terrain afterwards[16].

The final report points out that due to the fatigue of the crew and a sudden change from a runway which was fully equipped with the instrument landing systems (ILS) to a runway which has only the PAPI just prior to the final approach, they did not do the before landing briefing according to their standard operating procedures given by the company. When they flew the final approach, due to the captain's colour blindness he was failing to define the glideslope according to the PAPI light which was the only glideslope indicator on this runway. And due to the fatigue of the first officer, he was failing to monitor the final approach course and call out go-around when the PAPI indicates 4 red signals (See Figure 11). By the combination of those reasons, the captain flew the aeroplane into the total black hole illusions and eventually crashed into the trees prior to the runway [16].

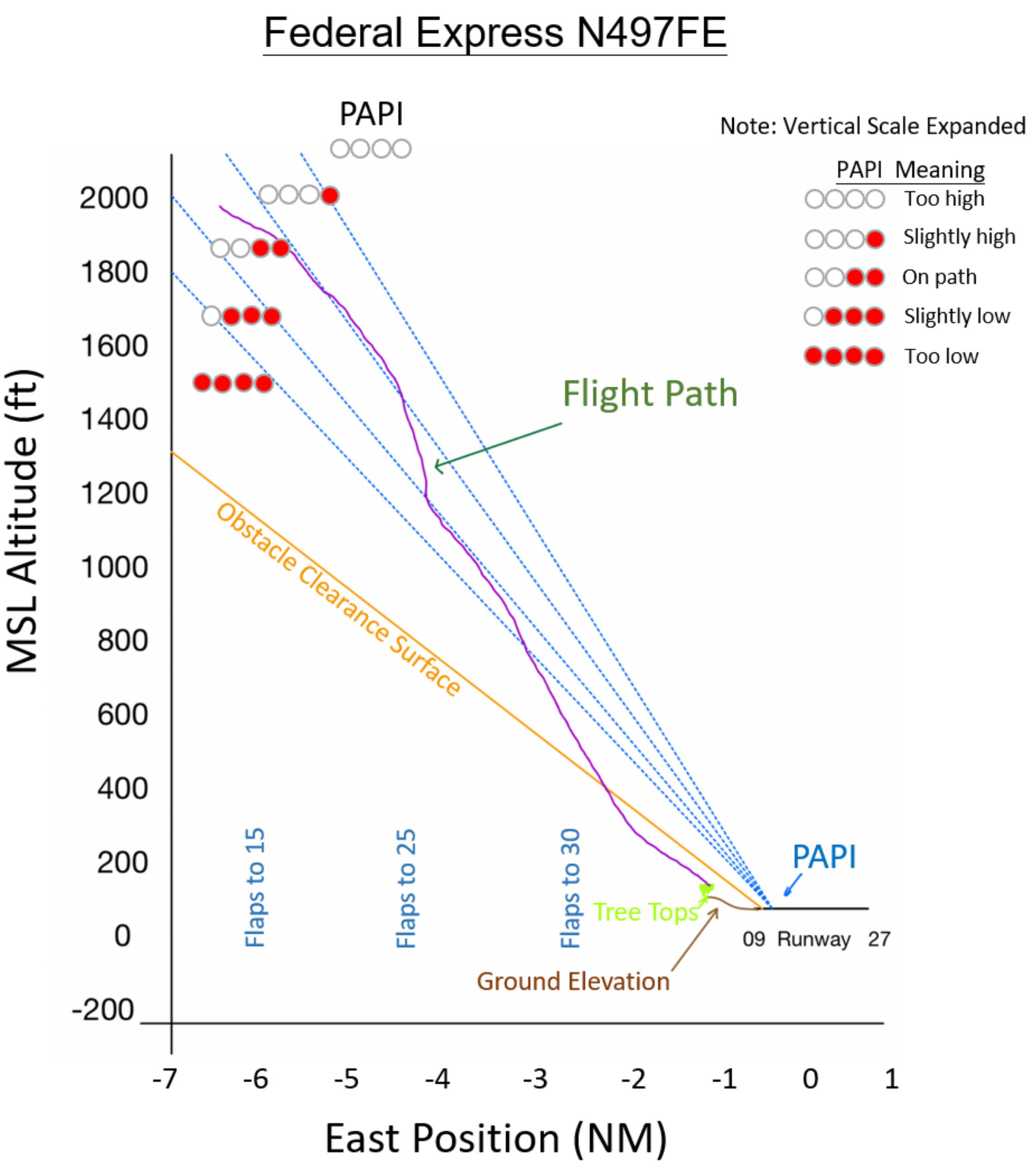

Figure 11: Glide path of Federal Express N497FE [16]

The accident of Beech-65-A90-1 with the registration Number of N7MC crashed at Slidell Airport happened on 19 April 2016, which is one of the closest air accidents caused by black hole illusions that happened these days [17]. It was clear weather with the visual condition and the runway is PAPI light equipped. The flight established the final approach track and did a visual approach. However, they flew lower than the glideslope without knowing and eventually crashed on the towers suspending high-power transmission lines [17].

The accident report found that both pilots were fully licensed and experienced. The PAPI at the airport was working properly at that moment. Probably because both of the pilots knew this was a regular flight to their home base airport, which led to crew complacency on their final approach. The pilot flying was not using the PAPI to fly the final approach course and his co-pilot didn't do the crosscheck to find out that as well, which led to the accident eventually happening.

1.3 Limitations of The Current State of the Art

Nowadays there are a lot of tools to guide pilots flying the defined glideslope. And the FAA's Pilot's Handbook of Aeronautical Knowledge (FAA-H-8083-25A), Chapter 10, "Night Operations," states that pilots at night shall always follow the instructions of either the navigation aids or the flight instruments [6]. For example, In the non-precision approach, the Continuous Descent Final Approach according to the altitude and distance instructions from the instrument as published in the Jeppesen Approach Plates, or in the precision approaches such as ILS or RNAV LPV, the instruments can simply indicate the position of the aeroplane according to the glideslope. In both cases, the clearance between obstacles and glide path is strictly calculated. If pilots could follow the instructions for glideslope altitude strictly, theoretically the risk of the collision with the ground can be easily removed. In most commercial airlines, airborne radar has a ground map mode which could indicate the height of the terrain and there is a GPWS working coordinating with the radio altimeter, to provide the true altitude with the ground.

Even though the accident of Pan Am 806 has multiple causes and due to the technical limitations of the 1970s, the final report was not even declared that black hole illusions are one of the causes of it, only mentioning that it may be one of the reasons. The accident of Federal Express Flight 1478 was a better example of the accident, due to the captain's disability on determine the red and white colour, he failed to monitor the PAPI indications, and probably due to the fatigue of his co-pilot who has not monitored the flight as well which led to the accident. The case of the Beechcraft flight was another proof of even though both pilots were healthy and experienced with the full guidance of so many instruments and charts, etc but the accident could still happen. Both the transition phase of the flight from instrument flying to the visual flying at the approach minimum decision altitude, and the visual approach during the night can still been affected by the visual illusions. So that the black hole illusions can still be a potential threat to flight safety.

The true cause of the black hole illusions is still in an argument, and for the visual approach part, the availability of the PAPI and the other instruments is still uncertain. Meanwhile, the limited amount of the available scientific literature describing the issues increased the certain constraints on the present review.

By the review of the current state of the art, it's not so hard to tell that the modern commercial flight with instrument flight rules phase doesn't really have the potential risk to the black hole illusions, however, during the transition at minimum decision altitude from IFR to the visual landing or in the general aviation flight with flying visual flight rules does. While piloting performance and all factors which affect it are significant to the flight safety concerns. However, there are still controversies over the causes of the illusion itself. The contribution of the ground-based glide path indicators such as the precision approach path indicator (PAPI) is not clearly defined. These limitations represent by the current state of the art shown associated with the issues that caused the loss of human life. In summary, the perceived effect of the black hole illusions during the approach and the function of the ground-based glideslope indicator creates the motivation for the present thesis. Therefore, the goal to present this thesis is to investigate the perception issue of the black hole illusions during the approach phase of the flight.

2. Materials and Methods

This chapter details the information about the research with regard to how the black hole illusions could affect the approach at night, compare the difference of the flight glide path with or without the PAPI and possibly find out the elements of the instruments which might cause the influence by using the Virtual Reality Flight Simulator (VRFS). The overall selection of the methods is based on the results of the current state of the art analysis and the goals mentioned in the first chapter.

2.1 Participants

This thesis investigated the perception issues of a night approach in the black hole conditions with the subjects of 52 volunteer basis. Even though most of the volunteers were already commercial pilot license holders, only a few of them were still in the integrated ATPL training course as student pilots, it is important to know that all of the volunteers are pilots with at least finished the EASA night VFR training or the holder of EASA night rating [18].

Even though there is a huge difference in the average experience of the participants, however, the goal of this task is to analyses the flight path by VR eye-tracking data and the pilot's experience on flight hours is not the concern of the task. All participants were issued the medical class 1 certificate to prove their physical and psychological fitness in accordance with the Commission Regulation (EU) No.1178/2011, Annex IV (Part-MED) [19].

Before the experiments, all participants were briefed about the general term and the procedure of the research, along with conditions of data collection and anonymization in accordance with the medical research of the human subjects. The participants' consent was secured by signing a data collection and processing agreement.

2.2 Experimental Setup

By the analyse of the current state of the art, the experiment has been set into the most ideal black hole situation. The initial position of the experiment been set at a point that is 8 NM to the runway threshold and 2500 feet above the ground, which is commonly used as a final approach fix to most airports. Such as exemplified in Figure 12.

Every experiment is preceded with a short brief including the aircraft type, current position, runway name and heading, current altitude, airspeed for approach and the goals, to make sure that all of the participants are able to understand their position and tasks. However, no additional instruction was provided, especially on the technique of flying according to defined instruments or constant runways shape, etc.

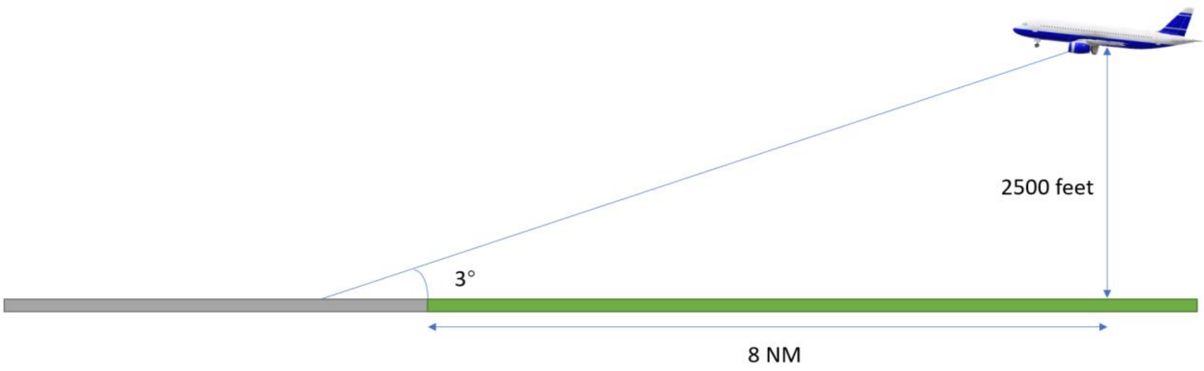

Figure 12: Initial set of the experiment

The way from the initial point to the runway at night is in total darkness the terrain won't be illuminated at all, and the stars and moon are not visible due to the graphic setting. The participants used the visual reality (VR) kit to improve 3D immersion and awareness. The aeroplane utilized within the experiments is the Beechcraft Baron 58, it is a multi-engine piston aeroplane with analogue gauges. And then the participants been asked to do four approaches to the runway: firstly, there was a free flight without recording in the daytime with the PAPI light on, only for them to get used to the simulator and the aeroplane. Then the first flight was also a flight in the daytime but without the PAPI light as the control group. The second flight is at night without the PAPI light as well, and the third flight would be at night with the PAPI light. The day and night switch among the function of the PAPI light are the only changed elements, and other experimental conditions remain unchanged, which can be predictable the tendency to the black hole illusion would be the only difference between the first and the second flight, and the function of visual guidance such as PAPI would be the difference between the second and the third flight (See Table 1).

Table 1: Experiments set-up

	Daytime	*Night*	*With PAPI*	*Without PAPI*
1st flight	X			X
2nd flight		X		X
3rd flight		X	X	

For maintaining the level of the complexity in the experiments and the consistency among the participants within the different experiments. The flight simulation is set in Karlovy Vary Airport (ICAO code: LKKV) with the Day time at 12:00 local time and the night-time at 00:00 local time. Due to the nature of the flight in this experiment being a visual flight, so the weather conditions have been set into VMC (Visual Meteorology Condition), visibility of more than 60 km, without any cloud, wind or turbulence (See Figure 13).

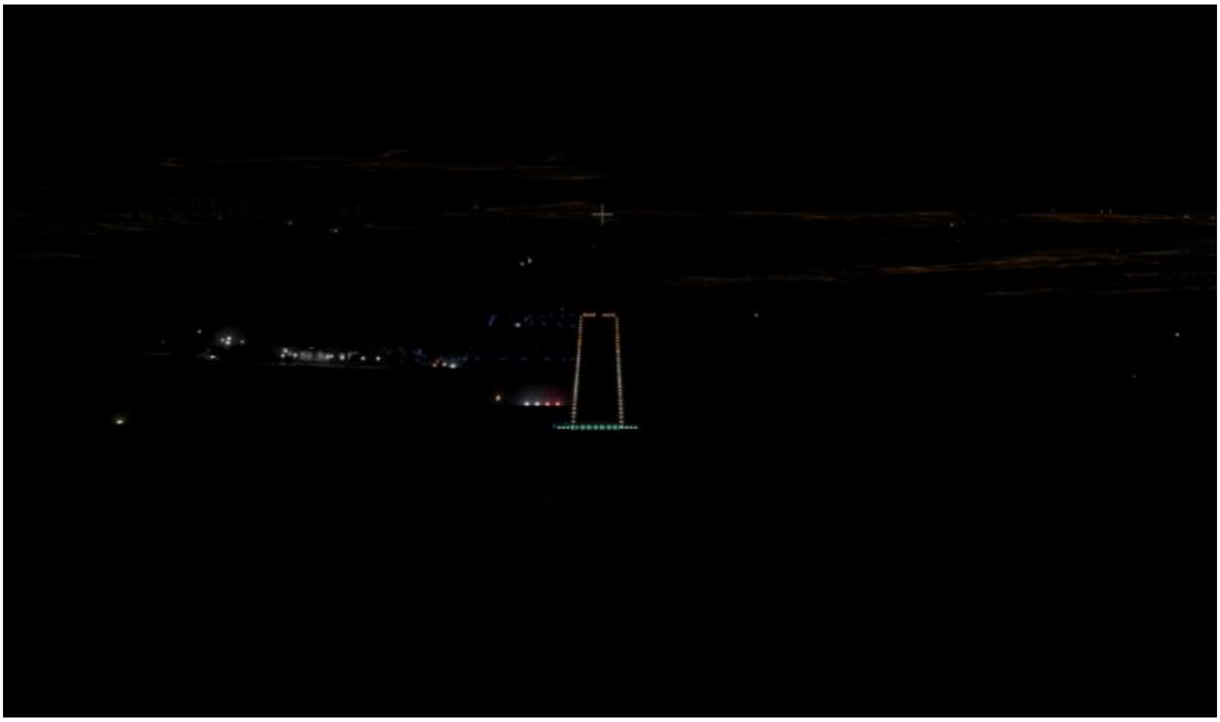

Figure 13: LKKV runway 29 from X-Plane 11

After landing each flight, the simulator has been reset to the initial point again, so the weight and balance of the aeroplane maintain the same to make sure that each flight would manoeuvre the same. And then the participants been told to fly with an airspeed of 110 kt with continuing descent flight. The participants are allowed to use all of the basic instruments including the airspeed indicator, attitude indicator, altimeter, turn coordinator, heading indicator for the function of marking the heading only, and the vertical speed indicator. The aircraft's undercarriage is already set prior to the beginning of the flight, and they need to set the flaps by their own. Every flight additionally involved landing portions flown by the subjects, however, landing is beyond the subjects of the task so they were not used for the purposes of data collection.

2.3 Equipment

As mentioned, this experiment has been done with the VRFS, so that, the equipment shall include VR parts and flight simulator parts. (See Figure 14) This is not the first time that VR products have been used in aviation, as VR display technology is maturing, the European Aviation Safety Agency (EASA) awarded the first certificate for Virtual Reality (VR) based Flight Simulation Training Devices (FSTD) in April 2021 [20]. The VR parts were supported by a FOVE0 VR headset (FOVE Inc., Tokyo, Japan).

Figure 14: A participant in the VRFS cockpit

This VR headset has a Wide Quad High-Definition Organic Light-Emitting Diode (OLED) 70Hz screen with a resolution of 2560x1440 plus 90°-100° of fields of visual and two eye-tracking systems tracking each of the eye focus points at the rate of 120 frames per second with an accuracy smaller than 1.15° deviations [21] (See Figure 15). The VR headset weighs 520g [21]. And the head movements can be captured by its own gyroscope.

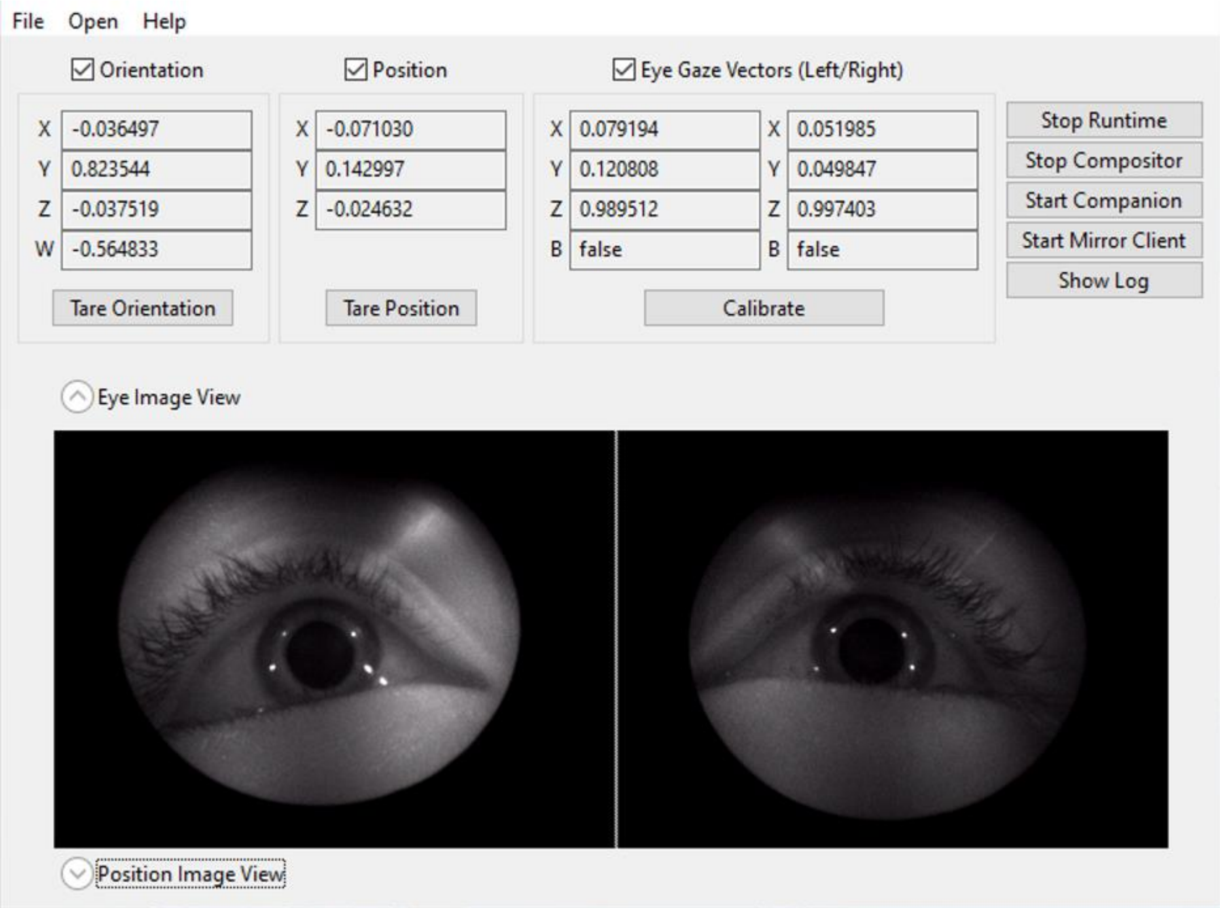

Figure 15: Fove eye tracking setup graphical user interface

The hardware of the simulator is been set on a platform with an adjustable seat and an integrated flight control system from Logitech (Logitech International S.A., Lausanne, Switzerland and Newark, California, U.S.). The system includes a yoke system, a thrust lever panel and a rudder system (See Figure 16). All of the control equipment is able to program or remove, so the levers been set into the order as in the real aeroplane which is from left to right in the order of throttle lever, propeller pitching lever and mixture lever, which simulate as much as the true perception of the flight control in the simulation.

Due to the software of the flight simulator and the other software which need the high performance of the calculation and the graphics calculations, the hardware of a computer as CPU - Intel Core i7-9700k - 3.6 GHz - 8 Core and 8 threads; Graphics card - Nvidia GeForce RTX 2080 Super; Memories - Corsair 32 GB RAM; Hard disk - 512 GB Solid-state drive is needed to perform the experiments [22].

Figure 16: Logitech flight yoke and rudder systems

The software used for flight simulation was the X-Plane 11 (Laminar Research Ltd., Columbia, South Carolina, USA). Models of the Beechcraft Baron 58 aeroplane flown is available by default with the simulator, the cockpit view is presented in Figure 17.

Figure 17: Cockpit of the Beechcraft Baron 58 in X-Plane 11

Virtual reality and eye-tracking flight simulators is been considered between the desktop simulator and the full functions of flight simulators for the research of human factors. It can provide the experience of a 3D cockpit with a headset to the test pilots and then capture their eye focus point movement without influencing the field of vision. To simulate the whole flight the tracking of head movement and hand movement could accomplish to interact with the virtual environment.

However, one of the disadvantages of this VRFS is that it is very hard to simulate the true tactile impression of the button on the dashboard for adjusting the sitting of the instruments, which is very important for the simulation of the IFR flight. Whereas, if the flight is only for the phase of the final approach after the final approach fix, in which all of the instruments are already set for landing, the pilot doesn't need to change anything but flying. In this case, the simulation could be more to the reality.

2.4 Data collection and pre-processing

The Data Record UI is an application made for the purpose of recording multiple sources of data, thus enabling data to be synchronized. Currently, it's been set to record the data from two sources. Firstly, is the Fove recorder application, which allows to record of the eye movement data from the Fove headset. Secondly, is the recording of the screen during the flight. When the application launches, it will ask the user to enter a file name, and it will be used for naming each of the files. Once when the user pressed the button "start recording", it will automatically create a file and upload everything which been recorded. And when the "stop recording" button is pressed, the recording will stop and all of the files will be saved.

The flight data has been recorded by an in-built application from X-Plane 11, it records the flight data at a sampling frequency of 5 Hz. The flight data has been recorded by time reference, which needs to be written manually by an operator. For the purpose of maintaining the data representation and its quality consistent for each subject, before each experiment began, a 30 seconds blank time has been set for the participants to awareness their position and prepare for their flight.

From the data obtained by the flight recorder, 3 variables are then extracted: Longitude, Latitude and altitude above the sea level. The initial data processing has been done by MATLAB (MATLAB R2022a, MathWorks, Inc., Natick, MA, USA). The focus of this experiment is the glideslope argument so that the aeroplane's horizontal movements relative to the runway have been neglected. For presenting the glideslope in two-dimensional space, in which the X-axis is the distance from the runway and Y-axis is the altitude above mean sea level. The distance data has been calculated by the coordinates of the aeroplane with the coordinates of the runway threshold, and the altitude data can be directly taken from the original flight data. Then the standard glideslope has presented as a red dotted line, which is 3 degrees extended from the runway threshold to the air as a reference. See Figure 18, the blue line is the glide path of the aeroplane and the red dotted line is the standard glideslope.

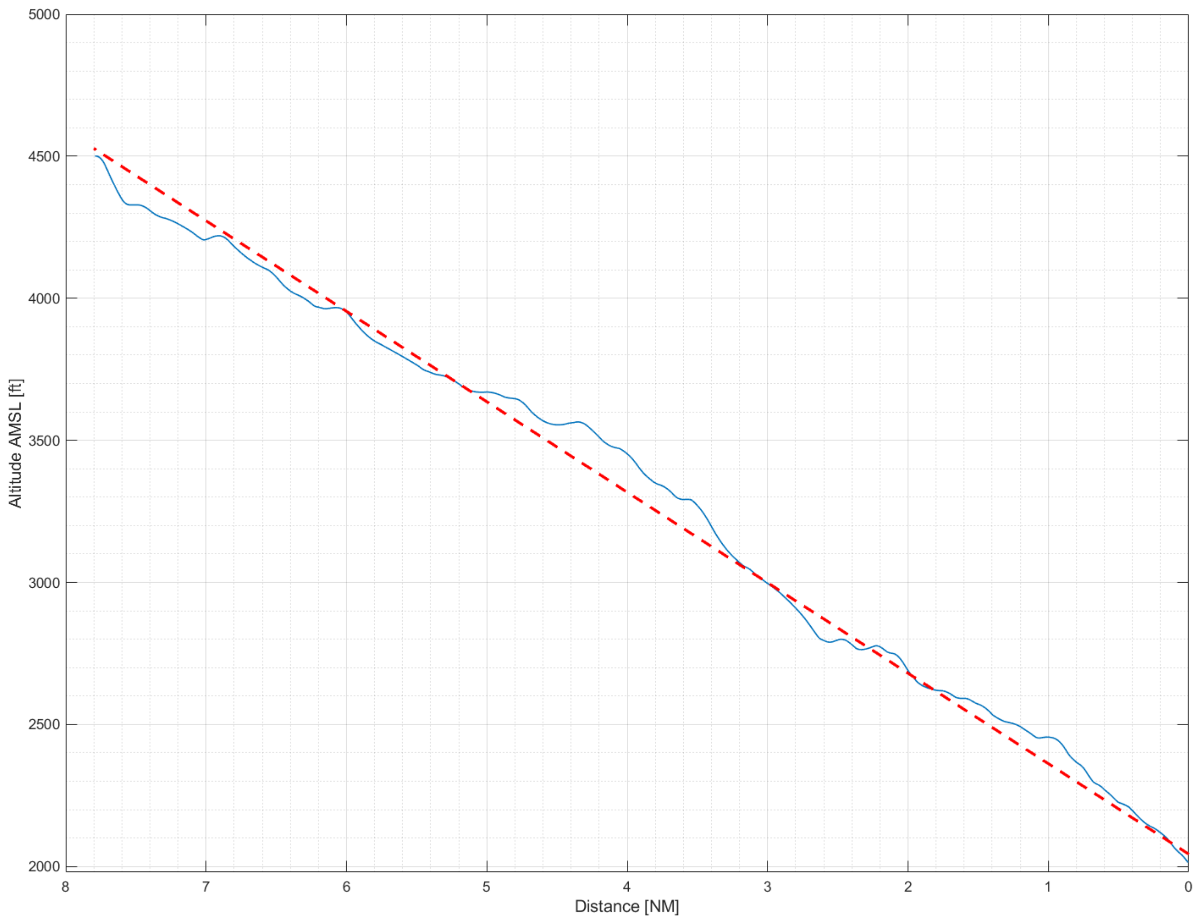

Figure 18: An example of the glide path

As mentioned above, the eye-tracking data is recorded in a two-dimensional coordinate system. Thus, the data is been presented in Two-dimensional coordinates. By outputting the coordinates into the cockpit panoramic view. The differences in colour saturation in the panoramic view of the cockpit to differentiate the dwell time of the eye focus is a feasible solution. However, the task is to find the interest region during the experiment of the instruments and analysis it according to the flight path, which means the function of the heatmap is not suitable due to the issues of the video files which complicates the creation of heatmaps.

It is well-known that Deep Learning has been developing rapidly in recent ten years due to the thrive of computer graphics process unit [23]. Compared to classical machine learning, deep learning takes longer time for training but can get far better results, and it is the mainstream in almost all computer vision tasks. Deep learning-based model, which is generally implemented by convolutional neural networks, was used for visual detection task. Region-Based Convolutional Neural Network (R-CNN) architecture is widely accepted to have a good performance on object detection and semantic segmentation tasks [24]. R-CNN contains three modules: the first one is responsible to generate category-independent region proposals, which are used as input for the second module, a large convolutional neural network, to extract high-level semantic features. The last module combines several classes specific linear support-vector machines and works as a machine learning classifier to correctly assign label to each class. Faster R-CNN inherits the idea of R-CNN but is implemented in a more efficient way, which takes full advantage of the ability of neural networks to extract high-level features [25]. Different with R-CNN, Faster R-CNN merges region proposal networks and Fast R-CNN into a single neural network by sharing their convolutional features with attention mechanisms, which accelerate training time substantially. Considering performance and efficiency, here the Faster R-CNN has been used as the main deep learning model. Alexnet [26], which consists of five convolutional layers and three fully connected layers, is the first neural network architecture to make deep learning famous and easy to implement, but still adopts some useful techniques like data augmentation and drop-out to improve prediction accuracy and reduce over-fitting problem, hence it been taken as the backbone of the main Faster R-CNN network.

The dataset used to learn the detector also includes images with marked regions of interest that are part of the Beechcraft Baron 58 aircraft instrument panel. These images were randomly selected from the total number of recorded video frames. The selection process for the training data was therefore carried out in such a way that: 40 videos were randomly selected from the total number of recordings (n=200). From each of the selected video recordings, a further 50 random frames were selected. In this way, 2000 RGB frames were taken in which regions of interest (ROIs) were marked (see Figure 19). The image resolution of the input dataset was 1920 × 1080 × 3. In each frame, the regions of interest were labelled with an image labelling program, which is part of the vision toolbox in MATLAB 2022a.

These areas specified the particular ROIs are the Airspeed indicator, Attitude indicator, Altimeter, Turn Coordinator, Heading Indicator, Vertical Speed Indicator, Engine instruments, thrust panel levers, Flaps selector, Windscreen and Runway. When the object detector was trained, it shall automatically recognize the instruments from the videos recorded from the experiments (See figure 20).

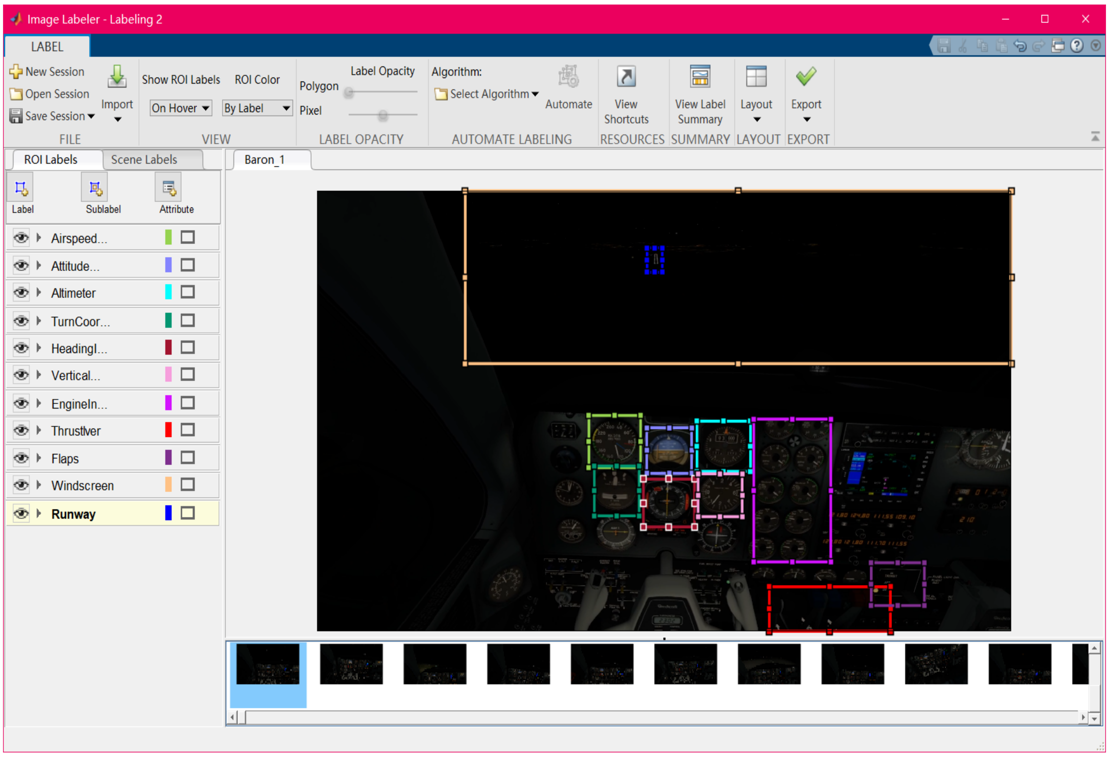

Figure 19: Example of a dataset created for training an object detector, with the region of interest marked

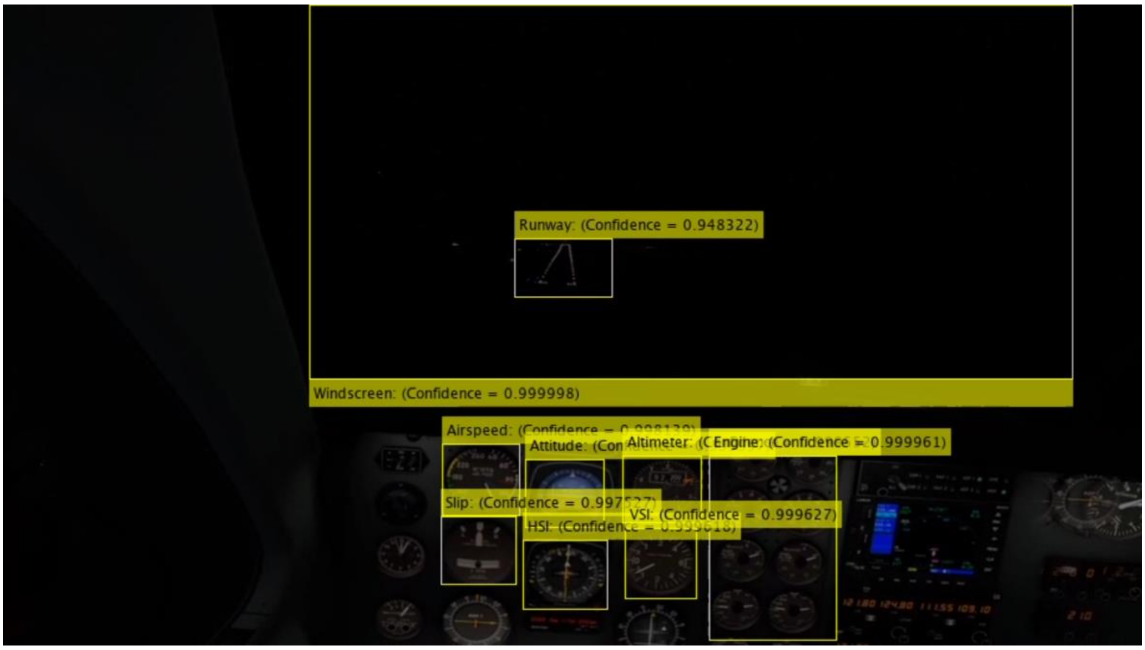

Figure 20: ROIs detected in the video

In the eye tracking system of a FOVE 0 headset, a 3-dimensional vector been used to represent the focal point of the human eyes. Then by putting the eye focal points data into the ROIs, the results can be presented as a percentage of the time the subject spent looking at the specified area.

With the glide path graph, it is possible to divide the subjects into two groups. The 1st group combines the subjects who have no significant deviation from the standard glideslope in the second experimental scenario and the 2nd group combines the subjects who did the flight with significantly lower than the standard glide path in the second experimental scenario. Due to the thesis only focusing on the lower than the standard glide path during the black hole illusions, so the eye tracking results of those who did a higher than the standard glide path have been neglected. Then by analysing the eye-tracking results between those two groups, the perception issues of the black hole illusions during the approach can be detected.

Figure 21: Example of the eye tracking distribution

Figure 21 shows the demo of the result in one experiment. The blue points shown on the frame represent the distribution of gaze positions. Here for simplicity, only one frame has been used for the explanation. As shown in the figure 21, during this special flight, this participant spent nearly half of the time on the windscreen i.e., looking for the runway.

2.5 Statistical Analysis

As the core purpose of this experiment is to define the perception issues of the black hole illusion during the approach. To achieve that, multiply experiments have been set. Therefore, the current statistical assessment is divided into two main sections based on the following objectives: analyse the effect of the black hole illusions during the approach phase and the function of the visual aids, and evaluate the perception issues of the black hole illusion by the analyse of the eye-tracking data.

2.5.1 Analyzation of the black hole illusions and the function of the visual aids

In the experiments of the three experimental simulation flights, the control variables method was used, they were analysed comparatively to determine if there were significant differences. The difference between the first and the second flight is for the purpose of defining the effect of the black hole illusions. The difference between the second and the third flight is for the purpose of defining the function of the PAPI.

In order to achieve an analysis of differences for the three experimental samples, the root-mean-square error (RMSE) of each flight data against the standard glideslope will first be calculated independently for each of the three experiments. The calculation of the RMSE can be performed as:

$$E=\sqrt{\frac{\sum_{i=1}^{n}(ALT_i-SALT_i)^2}{n}}, \quad (1)$$

Where E is RMSE for Altitude (ALT), ALT_i is the true altitude from the flight data collected at specific time points defined by sample i, $SALT_i$ is the standard altitude according to the current distance from the runway threshold calculated from the 3° glideslope.

Afterwards, the data of RMSE is arranged in the table in the order of the experiments. As the total sample size is the same for all three experiments and the samples are independent of each other, therefore, it enables the parametric statistical tools to be used for further analysis. The Friedman test has been selected to test whether there is a significant difference in the rank of each group of samples thus the difference between the piloting performance during the approach. The calculation of the Friedman test can be performed as:

$$X^2 = \frac{12}{nk(k+1)} \sum R^2 - 3n(k+1), \quad (2)$$

where n is the number of the subjects, k is the number of the experiments, R is the sum of the ranks. Chi-square distribution has been selected to compare get the p-value. Since hypothesis testing was performed at α=5 %, results with $p<0.05$ were considered as statistically different. And then, the Bonferroni correction by MATLAB was used for further post-hoc analysis to compare if there are any statistically significant differences between each of the flight glide paths.

2.5.2 Analyzation of the Eye-tracking data

The eye tracking data are presented in the percentage of time spent on the windshield to the total time. So that the Wilcoxon rank-sum test has been selected to check if the eye tracking distributions of the group that has no significant deviation from the standard glideslope and the group that did the flight significantly lower than the standard glide path are identical or not.

3. Results

The result of the statistic is presented in this chapter. They have been divided into two main parts: the glide path arguments and the eye-tracking arguments.

3.1 Generalized comparison of the glide path

The Figure 22 presents the glide path arguments of all three flights. The vertical axis presents the RMSE result of the vertical deviations from the standard glideslope in the unit of ft. For the sake of simplicity and clarity of the final data, all height data are rounded down to integer units.

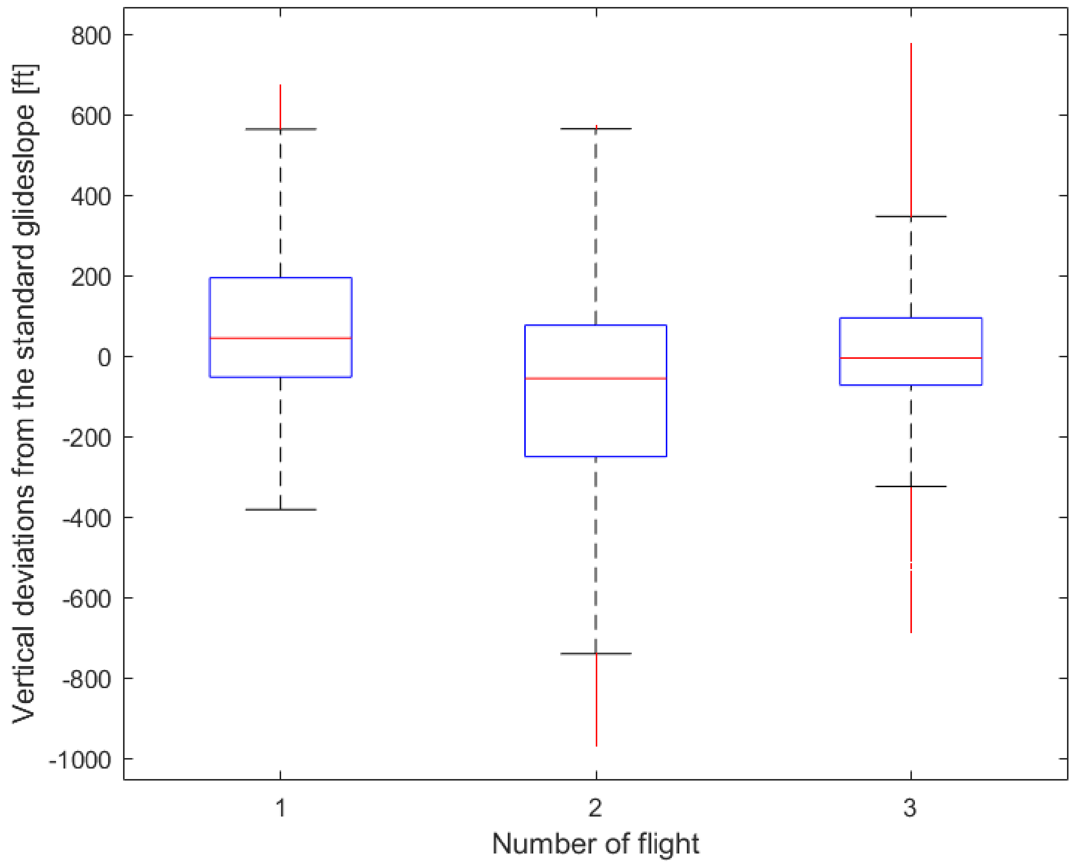

Figure 22: Glide path arguments of all three flights

The glide path analysis is presented below, the blue line is the glide path of the aeroplane and the red dotted line is the standard glideslope.

The RMSE result of the first flight presents the maximum deviation from the glide path as +672 ft and -382 ft. The 25th percentile in the data is -52 ft and the 75th percentile in the data is +195 ft with a median of +45 ft (See Figure 23).

The RMSE result of the second flight presents the maximum deviation from the glide path as +574 ft and -967 ft. The 25th percentile in the data is -250 ft and the 75th percentile in the data is +77 ft with a median of -55 ft (See Figure 24).

The RMSE result of the third flight presents the maximum deviation from the glide path as +780 ft and -686 ft. The 25th percentile in the data is -72 ft and the 75th percentile in the data is +96 ft with a median of -5 ft (See Figure 25).

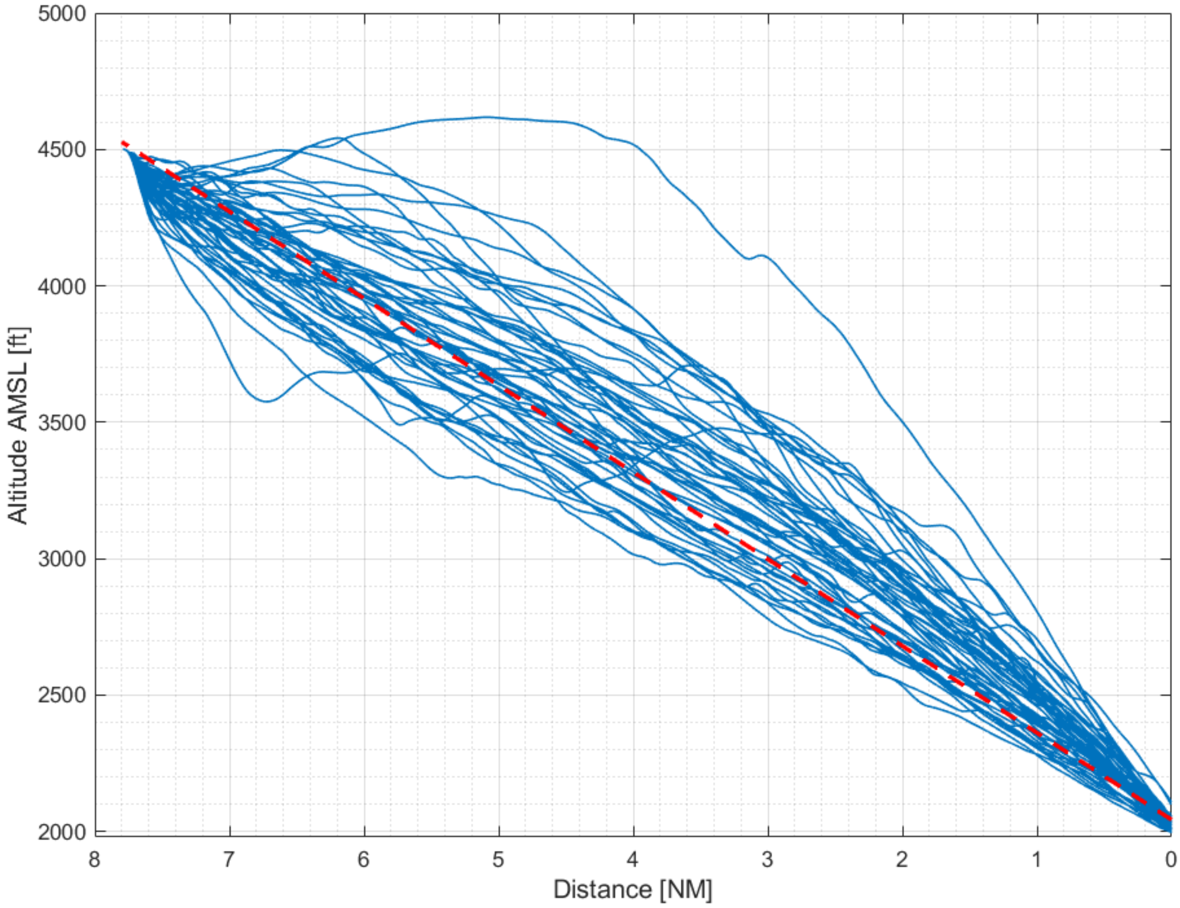

Figure 23: Glide path of the 1st flight

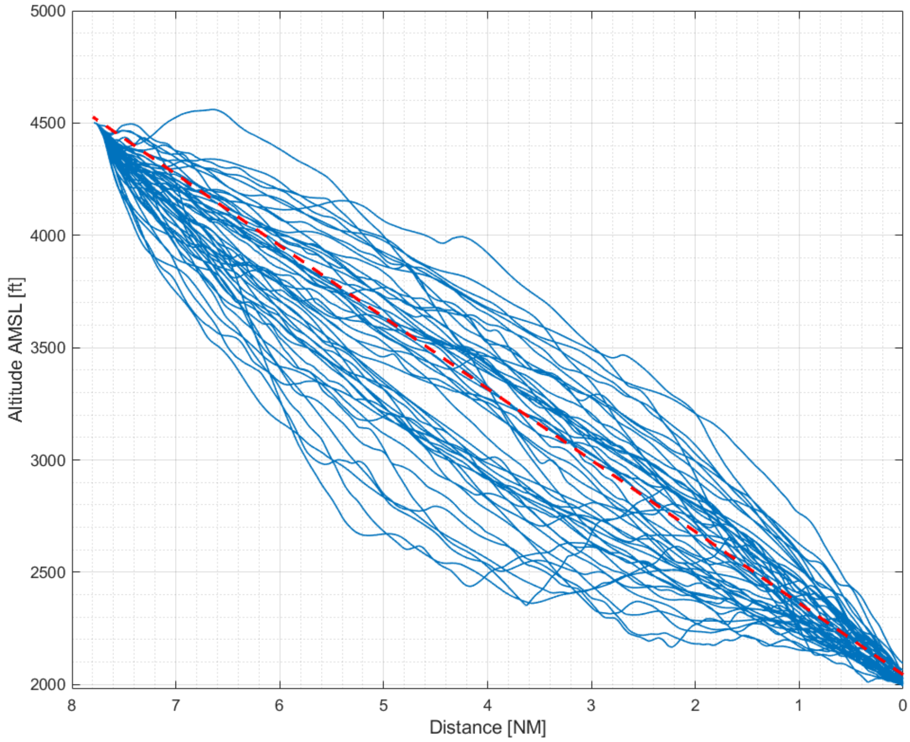

Figure 24: Glide path of the 2nd flight

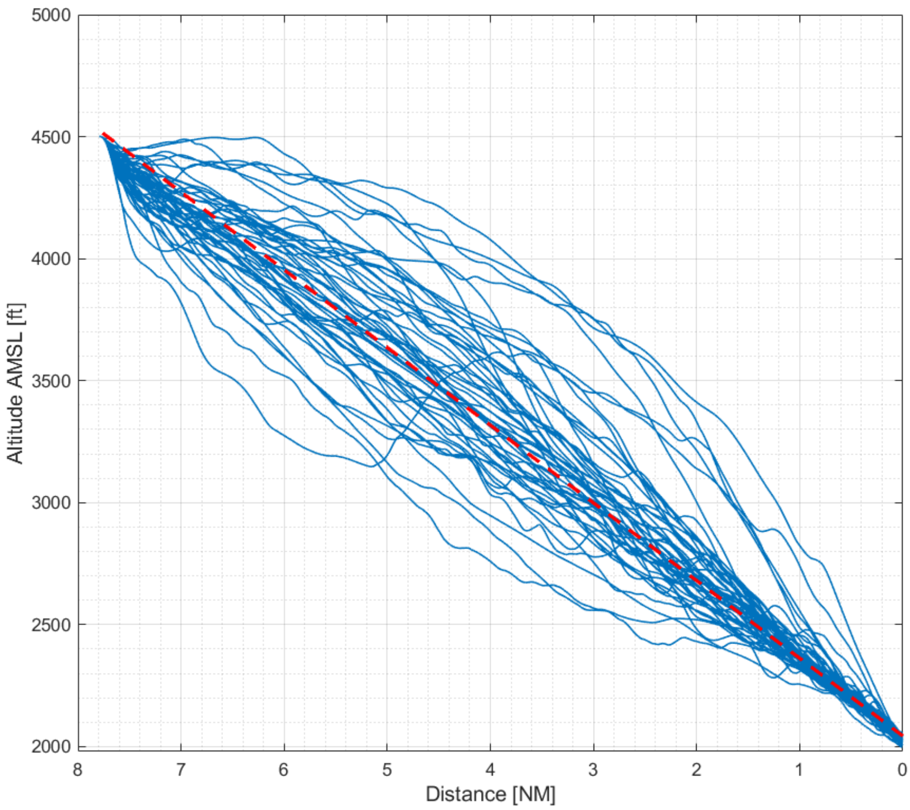

Figure 25: Glide path of the 3rd flight

3.2 The comparison between each of the flight

The monitoring of flight data allows pilot performance to be assessed with the help of several indicators. Friedman test indicates that χ (2,52) =12.8 and p=0.0017. Therefore, it indicates that significant differences between tested groups sample means exists (See Figure 26).

```
p =

    0.0017


table =

  4×6 cell array

    {'Source' }    {'SS'      }    {'df' }    {'MS'      }    {'Chi-sq'  }    {'Prob>Chi-sq'}
    {'Columns'}    {[12.8077]}    {[   2]}    {[  6.4038]}    {[ 12.8077]}    {[      0.0017]}
    {'Error'  }    {[91.1923]}    {[102]}    {[  0.8940]}    {0×0 double}    {0×0 double    }
    {'Total'  }    {[     104]}    {[155]}    {0×0 double}    {0×0 double}    {0×0 double    }
```

Figure 26: Result of the Friedman test

Post-hoc analysis using the Bonferroni method showed that statistically significant differences exist between the 1st and 2nd, also between the 2nd and 3rd flights. However, there are no significant differences between the 1st and the 3rd flights.

3.3 Eye tracking data analysis

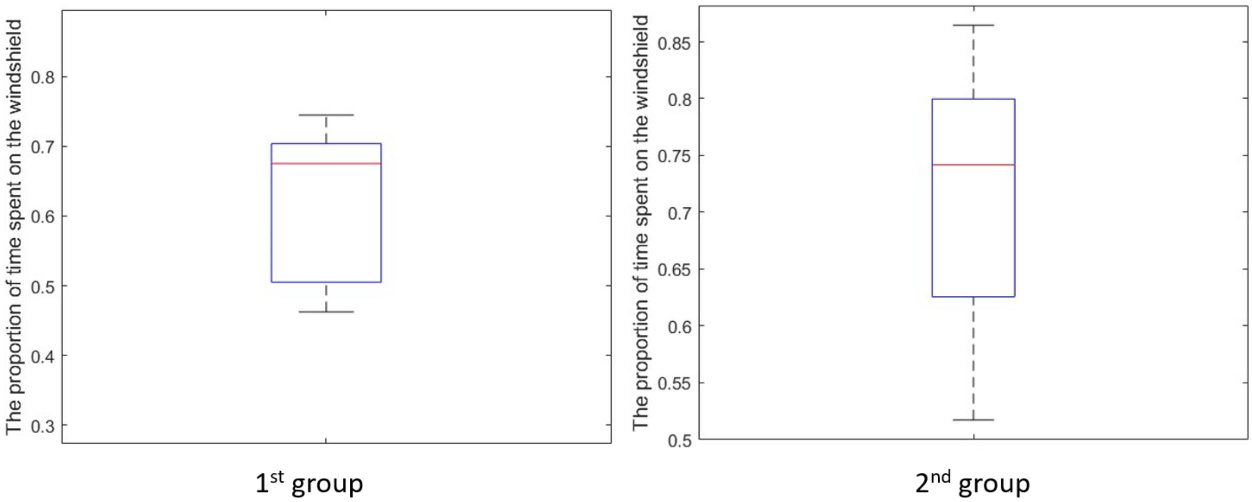

Figure 27:The eye tracking analysis of two groups

By analysing the eye tracking data from the two groups mentioned in the previous chapter, the differences between the proportion of time spent staring at the windscreen, data has been collected all needed for analysis, see Figure 27.

```
>> ET_test

p =

    0.0162


h =

  logical

   1
```

Figure 28: Result of the Wilcoxon rank-sum test

The 1st group of participants spent an average of 65% time on the windshield, the maximum and minimum time spent is 74% and 46%, the 25% and 75% of time spent is 51% and 70%. The 2nd group of participants spent an average of 71% of. time on the windshield, the maximum and minimum time spent is 86% and 51%, the 25% and 75% of time spent is 63% and 80%. The result of the Wilcoxon rank-sum test is p=0.0162 which indicates that rank-sum rejects the null hypothesis of equal medians at the default 5% significance level. Meanwhile, it also indicates that h=1 which means the distributions of the eye tracking data between both groups are not identical, see Figure 28.

4. Discussion

By reviewing the flight path graph, preliminary results were obtained. In the first experimental scenario with daylight, most of the participants preferred to fly higher than the standard glideslope, probably because they could clearly see the ground terrain and naturally wants to keep themselves away from it until they were close to the runway. When comparing the vertical component of the glide path of the first experimental scenario in daylight and without PAPI with the second experimental scenario at night and without PAPI, the majority of subjects tended to have a lower glide path in the second experimental scenario than in the first, which stands with the hypothesis of the effect of the black hole illusions mentioned in the first chapter. When comparing the glide path between the second experimental scenario and the third experimental scenario it was found that with the guidance of PAPI the majority of subjects tended to revert to the standard glide path in the third experimental scenario. The participant pilots were able to see the ground clearly and perceive the distance between them and the runway or the ground well enough to control the aeroplane with a good glide path to land during daylight hours, however, at night due to the poor illumination on the ground the pilot was unable to perceive his altitude through visual observation, which resulted in a wrong altitude judgement and a wrong descent path. When comparing the errors of the participants' glide path of all three flights, it indicates that with the assistance of PAPI, most of the participants could maintain a closer to the standard glideslope even at night. Even though the accident of N7MC happened with a fully functional PAPI equipped, however, there was no proves of that both pilots in the cockpit were focused on observing the PAPI. And in this experiment the contribution of PAPI is certain. At the same time, the fact that the lights scattered by the city beyond the runway were not involved in this experimental scenario. However, the fact that the black hole illusion caused the glide path to deviate was still present. So, it can be shown that even without the effect of the city lights beyond the runway, the black hole illusion can still affect the glide path, which denied the think of the black hole illusion due to the light effect of the city beyond the runway mentioned in the first chapter.

The Friedman test result indicates that there is a significant difference between the tested groups. And then the post-hoc analysis using the Bonferroni method indicated that the difference existed between the 1st and the 2nd groups and also between the 2nd and the 3rd groups. However, no significant difference was indicated in between the 1st and the 3rd groups. This seems to suggest that most of the participants were able to maintain a correct glide path with guidance from the PAPI, whereas once the guidance of the PAPI was lost, the participants had difficulty keeping the correct glide path, which stands with the conclusion of the accidents report of both Pan Am and FedEx Express. This may be due to the fact that some of the participants relied too much on using visual reference as the runway in the black hole conditions rather than flying visually with the aid of instruments. Whereas in the next experimental scenario with the PAPI as a guide for the glide path, even if the participants continued to fly with only the visual reference as the runway, they were able to easily observe the PAPI indication located next to the runway and thus adjusted the glide path with the PAPI guidance. And it is intuitively presented in the glide path analysis.

It is also found from the glide path analysis that in the second experimental scenario the largest value of deviation is found in the middle of the approach, and most of the participants were able to correct the glide path at the last few miles when they eventually saw the terrain illuminated by the runway light around the runway threshold, which stands with the theory that most of the perception of the black hole illusions happens in between the distance from 8.3 km to 0.9 km from the runway threshold mentioned in the first chapter.

By analysing the eye tracking data of the participants during the second experimental scenario, it is found that the distributions of the two data groups have statistically distinct differences. Those who flew almost on the standard glide path spent on averagely less than half of the time on the windshield i.e., they spent significantly more time monitoring the flight instruments, so that even if they perceived the black hole illusions during the approach they could still use the flight instruments to guide them to fly the correct glide path, this may be the reason why they could maintain their flight path on the standard glide path even without the help of any glideslope indicator. However, those who flew lower than the standard glide path spent on averagely more than half of their time on the windshield to look for the runway, because during the night without any illumination on the terrain, there is literally nothing that can be seen but the runway light and it can be inferred that they all perceive the black hole illusion and were affected by it. Thus, they all came up with a glide path lower than the standard approach, which stands with the theory of the black hole illusions due to runway light at night will affect the pilots' glide path mentioned in the first chapter. It is possible to conclude that during the night approach in a typical black hole illusions scenario, no matter in which rules of flight pilots shall always pay more attention to their flight instruments and if the visual glide path guide aids are available, monitor them carefully, especially during the middle of a long approach. So that the affections of the black hole illusions can be minimized.

5. Conclusion

This thesis discusses the perception issues of the "Black Hole" illusion during the approach and how its impacts the piloting performance. A thorough analysis of the current state of the art on this issue has revealed that even though there have been many flight safety incidents related to it over the last 50 years, there is still no conclusive knowledge on the cause of this Black Hole illusion. After totally studying the accident investigation reports of the Pan Am flight 806 crashed in Pago Pago International Airport, Federal Express Flight 1478 crashed in Tallahassee International Airport and a Beech-65-A90-1 crash at Slidell Airport, all of them were accidents caused by Black Hole illusions during the approach phase of the flight. The appropriate experiments and setups then were designed with the reference to those three accidents and 52 participants pilots were invited to fly these experimental simulation flights in accordance with the flight simulator and a VR headset. This is not the first time that VR products have been used in aviation, as VR display technology is maturing and the choice of using VR equipment for experiments is due to its flexibility and low cost. The parts of the flight simulator can be freely assembled in a modular way to match the different aircraft selected from the VR headset.

The aim of the experiment was to have the participants perform approaches in both daylight and ideal conditions for the formation of the Black Hole illusion. Then to record the flight data and perform statistical analysis in an attempt to explain the effect perception issues of the black hole during the approach. The judgement of the perception effect has been done by comparing the different actions of the same participants in different experimental scenarios. By comparing the flight data from the first and second experimental scenarios it is clear that the Black Hole illusion is objectively produced, even when without the light produced by the city beyond the runway. Thus, the hypothesis of the effect of city light beyond the runway being involved was dismissed. Analysing the eye tracking data from the second experimental scenario proves the hypothesis of the illuminated runway at night in the unilluminated terrain does affect the perception of pilots on the black hole illusions and if the pilot couldn't notice it by monitoring the flight instruments it will eventually cause a lower-than-normal approach, which is the potential risk of the flight safety if there is any obstacle exist below the flight glide path. And by comparing the flight data from the second experimental scenario with the third experimental scenario it can be learned that the accuracy of the piloting performance on the accuracy of night approach can be significantly improved due to the guidance of PAPI light. Again, by comparing the flight data from the first and third experimental scenarios, it can be concluded that the pilot's flying accuracy, when compared to the standard glideslope, was significantly improved with the guidance of PAPI even at night. So that the pilots shall be cautious about the situation and pay more attention to the flight instruments or the visual glide path aids if available, the effect of the black hole illusions then can be minimized.

Nevertheless, there are certain limitations that exist in this thesis. The VRFS is a brand-new technology, and even though it is one of the best ways to present a 3D cockpit to the participants, however, due to the limitation of the yoke simulator, it can't present the same handling stroke and the feedback of the air dynamic force as in a real aircraft. Even though the participants comment it was a precious night flying experience, however, most of them still need some time to get used to it, which may affect the accuracy of the data analysis. And then, according to the literature review, the effect of the black hole illusions is not only at night but also could happen in the daytime when flying over featureless terrain (such as standing water). But this thesis presents only the perception of the black hole illusions effect at night.

Based on the limitations stated, certain recommendations can be made for future research would be to build the experiments on a platform with dynamic force feedback and higher graphic resolution which has the possibilities for complex scenario settings. And the data collection shall not be limited to the aeroplane movement itself, but also the pilots' manoeuvre input for a better analysis of the perception of the pilot. In the eye-tracking part, if the analysis can be done with the plot of the eye movement tracks technologies and the analysis of the distribution of gaze positions can be done on not only the windshield but also every instrument, the result of the perception issues of the black hole illusions may be more intuitively present.

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