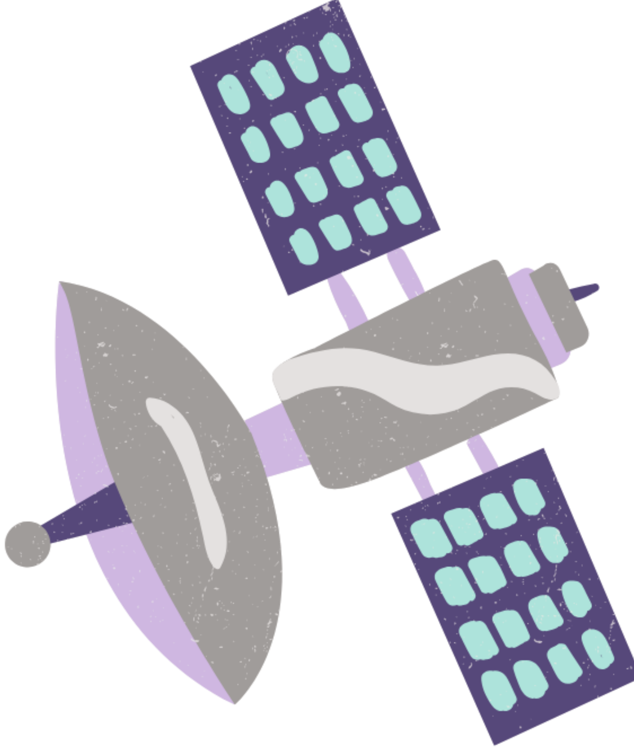
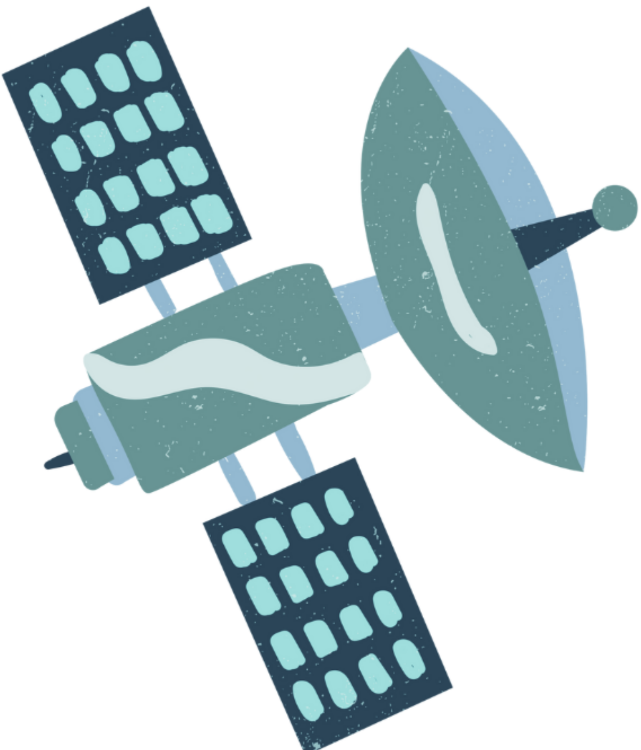


Quality analysis of Global Navigation Satellite System signals in the Netherlands using aircraft derived data

Thesis



Pam Smit

500882997

Schiphol-Oost, June 2025

Final Report – Quality analysis of Global Navigation Satellite System Signals in the Netherlands using aircraft derived data.

June 2025

Schiphol-Oost, Netherlands

P.M. Smit

500882997

Amsterdam University of Applied Sciences

pam.smit@lvnl.nl | pam.smit@hva.nl

Company supervisors

B. Banning

K. Noordeloos

Luchtverkeersleiding Nederland

Academic supervisor

A. Murrieta Mendoza Ph.D.

Amsterdam University of Applied Sciences

Abstract

The integrity of Global Navigation Satellite System (GNSS) signals is critical to the safety and efficiency of modern aviation, particularly as reliance on satellite-based navigation and surveillance systems continues to grow. This thesis investigates the quality of GNSS signals in Dutch airspace by analysing Automatic Dependent Surveillance-Broadcast (ADS-B) data collected between January 2025 and May 2025. The study focuses on two key ADS-B parameters, the Navigation Integrity Category (NIC) and the Navigation Accuracy Category for Position (NACp), to assess the quality of the GNSS signal quality.

Using regulatory thresholds established by the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA), the analysis identifies NIC values below 7 and NACp values below 8 as indicators of poor GNSS performance. The dataset, sourced from Luchtverkeersleiding Nederland (LVNL), includes four months of historical ADS-B transmissions, which were cleaned, merged, and analyse. Visualizations and statistical tests were employed to explore correlations between signal degradation and factors such as flight category, operator origin, and geographic location.

Results show that while the majority of ADS-B transmissions meet regulatory standards, 88.5% of NIC values were 8 and 93.4% of NACp values were 9 or higher, approximately 1.8% of NIC values and 0.6% of NACp values fall below acceptable thresholds. Further analysis reveals that general aviation contributes disproportionately to poor NIC values, particularly in recreational airspace regions such as Northern Noord-Holland and Zeeland. Additionally, operators from Asia, despite comprising only 6.4% of the dataset, account for over 30% of poor NIC transmissions. A two sample t-test confirms this disparity with a statistically significant p-value of 0.0008, suggesting a trend with operators from Asian origin and GNSS signal degradation.

These findings underscore the need for continuous monitoring of GNSS signal quality and highlight the potential for ADS-B data to serve as an early warning system for signal interference. The study recommends future use of ADS-B datasets with the inclusion of aircraft type, flight routes, and more, to develop real time dashboards to detect emerging threats.

List of Abbreviations

Table 1: List of Abbreviations

ADS-B	Automatic Dependent Surveillance Broadcast
ATC	Air Traffic Control
CNS	Communication Navigation Surveillance
CSV	Comma-Separated Values
EPU	Estimated Position Uncertainty
FAA	Federal Aviation Administration
FIR	Flight Information Region
GA	General Aviation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LVNL	Luchtverkeersleiding Nederland/ Air Traffic Control the Netherlands
MEO	Medium Earth Orbit
NACp	Navigation Accuracy Category for Position
NACv	Navigation Accuracy Category for Velocity
NaN	Not a Number
NIC	Navigation Integrity Category
PPS	Precise Positioning Service
RC	Containment Radius
RFI	Radio Frequency Interference
RNAV	Area Navigation
SPS	Standard Positioning Service
TOA	Time of Arrival
UTC	Universal Time Coordinated

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1. Introduction

1.1 Background Information

On Christmas day 2024 an Azerbaijan Airlines planes crashed in Kazakhstan, at least 38 of the 67 people on board were killed in the crash. Shortly before the plane lost control, the crew had reported a loss of Global Positioning System (GPS) signal to air traffic control (CBS, 2025). There has been a notable increase in the interference of GPS since February 2022, particularly in regions surrounding conflict zones (EASA, 2024).

In 1973 the U.S. Department of Defense developed the GPS project, with a total of 24 satellites, GPS would overcome the limitations that previous navigation systems had (Hempisphere, sd). GPS is an example of a Global Navigation Satellite System or for short GNSS, this is any satellite constellation that provides positioning, navigation, and timing services on a global scale (EUSPA, 2025). While GPS is an American constellation there are other available GNSSs such as the European Galileo, the Russian GLONASS, and the Chinese BeiDou. GNSSs form a key technology in the Communications, Navigation, and Surveillance (CNS) infrastructure (Eurocontrol, sd). Aircraft use GNSS to fly Area Navigation (RNAV) during all phases of flight (Navigation Programs - Satellite Navigation, sd), as well as surveillance applications such as ADS-B. Using GNSS ensures accuracy in position, speed, and time, integrity, continuity of service, and availability (Eurocontrol, sd).

Since the GNSS consists of satellites that fly in the medium earth orbit, the signal received from the satellites is very low in power and therefore vulnerable to interference (CAA, 2009). Jamming and spoofing are ways to interfere with the GNSS signals. A spoofer intentionally transmits fake signals, which are similar to authentic signals to the receiver. Fake signals are transmitted at higher power than authentic ones in order to trick the receiver into picking up those signals and eventually begin tracking the fake satellites. Resulting in the attack taking over the receiver's navigation system and forging its location. Jamming is an intentional transmission of a high-power radio frequency signal equal or very close to the frequency of the device whose operation is to be prevented. A jamming attack aims to prevent the receiver from collecting and tracking GNSS signals and navigating using GNSS signals (Radoš, Brkić, & Begušić, 2024). Both jamming and spoofing principles are depicted in figure 1.

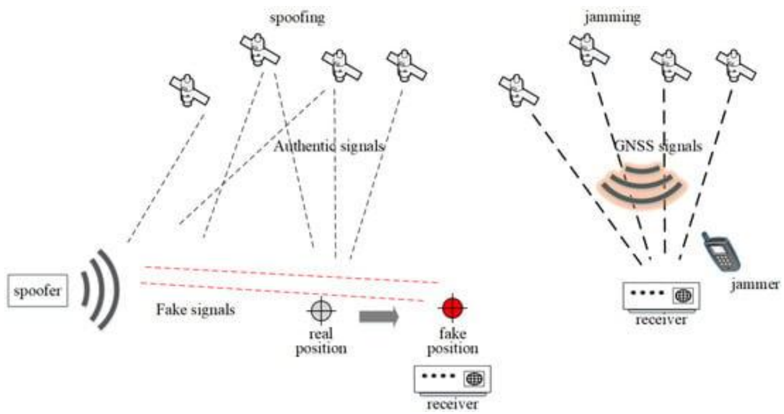

Figure 1: Jamming and Spoofing Principles (Radoš, Brkić, & Begušić, 2024)

Automatic Dependent Surveillance - Broadcast (ADS-B) provides a highly accurate and effective means for air traffic controllers to accommodate air traffic surveillance services outside of radar coverage. An aircraft with ADS-B determines its position using GNSS, the aircraft then broadcasts that position at rapid intervals, along with identity, altitude, velocity and more, shown in figure 2. Dedicated ADS-B ground stations can receive the broadcasts and relay the information to ATC for precise tracking of the aircraft (Eurocontrol, sd).

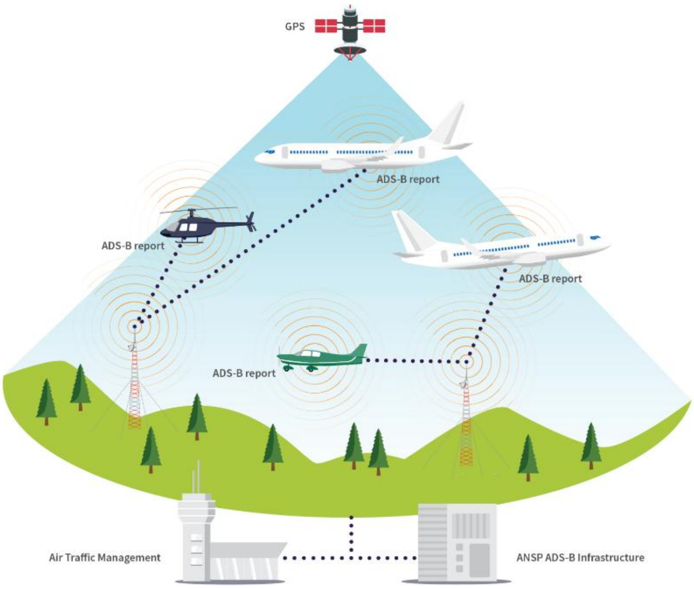

Figure 2: ADS-B system overview (Civil Aviation Authority Of New Zealand, sd)

ADS-B data also contains parameters called Navigation Accuracy Category (NAC) and Navigation Integrity Category (NIC), the NIC coding is used to indicate the containment radius around the aircraft. The containment radius means that there is a 95% probability that the aircraft is within that radius of its stated position (ICAO, 2022). The NIC parameter has been proved to detect GPS jamming, however it is not a reliable indicator for spoofing detection (Navigation Systems Panel, 2024). A NIC value greater than 7 is a good value, meaning that the aircraft probably did not experience jamming, an average NIC is between 5 and 7, and a bad NIC is below 5, meaning that there is a great chance that spoofing occurred (SKAI Data Services, 2025). GPS spoofing can be detected by identifying anomalies like sudden changes in the reported aircraft positions or unrealistic speeds (Navigation Systems Panel, 2024).
Air Traffic Control the Netherlands (LVNL) wants to use data analysis of the ADS-B data to get an overview of the GNSS quality in the Netherlands. Due to the growing use and dependence on GNSS in aviation a loss of navigation would be a safety issue. It is for that reason that it is needed to investigate if, and for what duration the GNSS signal degradation occur in the Dutch flight region.

1.2 Problem Statement

The increasing interference with GNSS signals, particularly in regions surrounding conflict zones, poses a significant threat to aviation safety. Given the growing reliance on GNSS for navigation and surveillance in aviation, it is crucial to analyse the quality and reliability of GNSS signals in the Netherlands. Currently there is no complete insight in the quality, occurrence, and regional characteristics of the GNSS signals in the Netherlands.

1.3 Main Objective

This thesis aims to investigate the occurrence of GNSS signal disruptions using ADS-B data to ensure the safety and integrity of air traffic control operations. An overview should be provided of the Dutch airspace showcasing various factors that correlate with the variations in GNSS signal quality.

1.4 Sub-Objectives

To reach the main objective, the following sub-objectives are established:

- Identify what the criteria are for an occurrence to be flagged as dissatisfactory. Defining the specific thresholds and conditions under which an area is considered to have poor GNSS signal quality, by looking at preset international standards.
- Identify patterns, trends, and specific attributes of the ADS-B data. Patterns and trends can be identified of the NIC values, visualisation will provide insight in the quality of the GNSS signals and correlations between the NIC values and other parameters.
- Provide an overview to get a clear insight of the quality and reliability of GNSS signals in the Dutch airspace. Developing an overview to showcase the visualisations of the analysed data. This reporting should give a clear insight in the quality and reliability of the GNSS signals and the airspace where the quality was low.

1.5 Research and Sub-Questions

"What is the occurrence, duration, and location of GNSS signal disruptions in the Dutch airspace as indicated by ADS-B data?"

- How do international aviation standards guide the classification of dissatisfactory NIC values?
- What patterns, trends, and specific attributes can be identified in the ADS-B data related to GNSS signal disruptions in the Dutch airspace?
- What are the key contributors to variability in the quality and reliability of GNSS signals in the Dutch airspace?

1.6 Scope and Limits

The scope of this thesis makes sure that the research is not too broad and can be successfully finished in five months. The scope of this thesis consists of:

- This thesis solely focusses on data analysis of the ADS-B data, everything surrounding GNSS and the jamming and spoofing of GNSS is background information.
- The data that is going to be used for the overview is ADS-B data that has been received in the Dutch Airspace.
- The visualisations will be created using historical data and will not be using live data.

This thesis can encounter the following limitations:

- Noise in the data
  ADS-B data can contain noise, it is not certain that every aircraft transmits the right data, most noise can be filtered during data cleaning, but there is a chance that not all noise can be filtered out.
- Data availability
  The data used for this thesis is owned by LVNL, therefore the research can only be done with the data that is available, this can be more or less data than expected.

- Limited timeframe
  This research is conducted within a limited timeframe of five months. It is important to scope the research correctly to ensure it is not constrained by the available time.

2. Preliminary Theoretical Framework and Literature Review

2.1 Theoretical Framework

Global Navigation Satellite System (GNSS) provides accurate, continuous, worldwide, three-dimensional position and velocity information to the users, it also transmits time within the Coordinated Universal Time (UTC). The Global constellations within the GNSS consist of 24 or more medium Earth orbit (MEO) satellites, that are arranged in three or six orbital planes, with four or more satellites per plane. MEO is a class of orbits that typically range in the 10,000 o 25,000 km altitude. GNSS uses the concept of time-of-arrival (TOA) to determine the user position. This entails measuring the time it takes for a signal to be transmitted by an emitter at a known location to reach a user receiver. This time interval, also known as the signal propagation time, is then multiplied by the speed of the signal propagation to obtain the emitter to receiver distance. By measuring the propagation time of signals broadcasted from multiple emitters at known locations, the receiver can determine its position (Kaplan & Hegarty, 2017).

Global Positioning System (GPS) has been developed in the United States of America in the 1970s, GPS is an example of a GNSS. GPS provides two primary services Precise Positioning Service (PPS) and Standard Positioning Service (SPS). PPS is an encrypted service that is intended for military and other authorized government users. SPS on the other hand is free of direct user fees and is in use by billions of civil and commercial users worldwide. Both services provide navigation signals for a user to determine position, velocity, and UTC. The GPS constellation consists of 24 satellites in six MEO orbital planes (Kaplan & Hegarty, 2017). In the aviation industry GPS is used in aircraft for the navigation, it provides the ability to fly point-to-point, instead of following ground based radio navigation. GPS in combination with map details give the ability to orient the aircraft relative to their flight path, terrain, obstacles, and weather (GPS Innovation Alliance, 2023).

GNSS signals can experience interference, as introduce in Chapter 1, this is the (un)intentional disruption of the GNSS signal. The interference can happen in two forms jamming and spoofing. Jamming is an interference with GNSS signals using radio frequency signals on the same frequency as the GNSS signal. This disrupts or blocks the GNSS signals, resulting in GNSS devices and systems being unable to provide accurate positioning and navigation information. Spoofing is a deceptive technique where signals are created to mimic legitimate GPS signals. These counterfeit signals can trick GNSS receivers into providing false or manipulated location information. This may result in the user believing they are on a different trajectory than they actually are. Both jamming and spoofing can lead to dangerous situations, the consequences of the GNSS outages are unpredictable and can significantly impact aviation operations (MIDANPIRG Air Traffic Management Sub-Group, 2023). Jamming and spoofing are examples of intentional disruption of the GNSS signals, but unintentional signal interference can also happen. This type of interference can stem from diverse sources, such as television signals, specific radar systems, mobile satellite communications, military equipment, and more (MIDANPIRG Air Traffic Management Sub-Group, 2023).

An aircraft with Automatic Dependent Surveillance-Broadcast, or ADS-B for short, determines its position using GNSS. ADS-B is a satellite based surveillance system that relies on aircraft that broadcast their identity, position, and other information derived from their onboard systems. This signal can be picked up on the ground (ADS-B Out) or on board of other aircraft in order to facilitate airborne traffic situational awareness such as spacing, separation, and self-separation (ADS-B In). ADS-B is dependent because it relies on on-board systems to provide surveillance information to other parties with no external input required. The data is broadcasted, so the original source has no knowledge of who receives the data and there is no two-way contract (Eurocontrol, sd). Currently three versions of ADS-B exist, version 0, version 1, and version 2. Each version is a newer and improved version of the previous version. As operational knowledge was gained, a transition was made from event-driven messages to periodic messages. The newer the version, the more parameters the ADS-B broadcasts (Rodriguez, 2018). Within the ADS-B data the Navigation Integrity Category (NIC) and Navigation Accuracy Category (NAC) can be found. The NIC value is used to indicate the containment radius around the aircraft. NAC can be divided into two categories NACp and NACv. NACp stands for Navigation Accuracy Category for Position, this indicates the accuracy of the position of the aircraft that is transmitted. NACv stands for Navigation Accuracy Category for Velocity, this indicates the navigation accuracy for the velocity of the aircraft that is transmitted (ICAO, 2022). NACp and NIC give a good indication when GNSS-based navigation is lost, as both parameters decrease as a consequence (Figuet, Waltert, Felux, & Olive, 2022). In table 2, the Estimated Position Uncertainty (EPU) for each NACp value can be found, this is a measure that indicates the estimated performance of the current position of the aircraft, the EPU is not an estimate of the actual error but a defined statistical indication of potential error (ICAO, 2013).

Table 2: NACp parameters and their values for ADS-B version 1 and 2 (Sun, 2021)

NACp	Estimated Position Uncertainty (EPU)
11	<3 m
10	<10 m
9	<30 m
8	<93 m
7	<185 m
6	<556 m
5	<926 m
4	<1852 m
3	<3704 m
2	<7408 m
1	<18520 m
0	>18520 m or Unknown

In table 3, the Horizontal Containment Radius Limit (RC) can be found for each corresponding NIC value, the RC is the radius within which there is a 95% probability that the aircraft is within that radius of its stated position.

Table 3: NIC parameters and their values for ADS-B version 1 and 2 (Sun, 2021)

NIC	RC
11	<7.5 m
10	<25 m
9	<75 m
8	<185 m
7	<370 m
6	<1018 m
5	<1852 m
4	<3704 m
3	<7408 m
2	<14.8 km
1	<37.0 km
0	>37.0 km or Unknown

2.2 Literature Review

In 2012, researchers Sam Pullen and Grace Xingxin Gao explored the potential threats that GNSS jamming poses to aviation. They highlighted that while the emergence of multiple interoperable GNSS constellations offers significant benefits for positioning and navigation, these systems remain susceptible to interference, especially from ground-based sources. This vulnerability is partly due to the need for aircraft to track low-elevation GNSS satellites in order to achieve optimal satellite geometry, which increases the likelihood of encountering interference from terrestrial sources (Pullen & Xingxin Gao, 2012).

A few years earlier, in 2009, a related study investigated the impact of GPS jamming on maritime navigation. The research demonstrated that even low-power jammers could lead to service denial, either deliberately or unintentionally, exposing the fragility of GPS in critical settings. Similar to the aviation sector, maritime crews often expect GPS to perform flawlessly, which means that failures caused by interference may go unnoticed until they have serious consequences. This lack of awareness can significantly impact safety and operational reliability (Grant, Williams, & Basker, 2009). While the focus was on maritime environments, the findings closely parallel concerns in aviation, where pilots, air traffic controllers, and ground staff also heavily rely on GPS. A sudden loss or degradation in service can increase workload and compromise safety.

More recent research has shifted toward not just identifying jamming threats but also localizing their sources. In 2022, a study demonstrated how ADS-B data could be used to detect and locate GNSS interference. By analysing the NIC values in ADS-B data, where regulations require a minimum NIC value of 7, researchers found that clusters of data points with NIC values below this threshold could indicate the presence of an RFI source. A mathematical model incorporating signal line of sight and power levels was then used to triangulate the location of the interference (Liu, Lo, & Walter, 2022).

The same group of researchers also conducted a study in 2021, this was thy first research to apply deep learning techniques to ADS-B data for interference detection and localization. Researchers developed two machine learning models: a standard neural network to estimate the size and shape of the jammer's impact zone, and a convolutional neural network to pinpoint the most likely source of the interference. These models require only a few hours' worth of ADS-B data from the target airspace to produce reliable results. The models classify whether an aircraft has experienced jamming, offering a data-driven approach to a growing aviation safety concern (Liu, Lo, & Walter, 2021).

Together, these studies underscore the urgent need for resilient navigation systems and robust interference detection tools. As reliance on GNSS continues to grow in both aviation and maritime sectors, recognizing and mitigating the risks of RFI becomes increasingly critical to ensure the safety, reliability, and efficiency of modern transportation systems.

3. Methodology

Quantitative research was conducted to create insight in the quality, occurrence, and regional characteristics of the GNSS signals in the Netherlands. The first sub-chapter 3.1 covers the approach to find the criteria for the thresholds. Sub-chapter 3.2 explains how the ADS-B data used for this thesis is collected and sub-chapter 3.3 gives a detailed description of the data. Sub-chapter 3.4 entails the methods of data analysis used for this thesis. Lastly, sub-chapter 3.5 explains the statistical testing.

3.1 Criteria for the Thresholds

The first threshold that was set was to determine when the GNSS signal was considered poor quality, for example identifying which NIC value indicated degraded GNSS quality. This was achieved by reviewing existing aviation standards and regulatory definitions for specific values in the ADS-B data. The second threshold focused on defining the acceptable ratio between good and poor quality signals. This was determined by analysing the overall data to calculate an average baseline, which served to identify what constitutes an unsatisfactory ratio. This threshold was applied both to assess specific geographical areas and to compare the performance of different operators

3.2 Data Collecting

For the data collection ADS-B data from an internal LVNL source called the Surveillance Data North-Sea (SDNS) system is used. This system is designed with the primary goal of obtaining low altitude surveillance coverage over the North Sea. The SDNS system processes both Wide Area Multilateration (WAM) and ADS-B data (LVNL, 2024). The system has 15 ground stations and 5 other stations, consisting of weather stations and lighthouses, that are operated by Rijkswaterstaat, together they give the coverage shown in figure 4. In figure 3 the locations of the different units are shown, this includes both WAM and ADS-B stations.

Figure 3: ADS-B Stations Locations (LVNL, 2024)

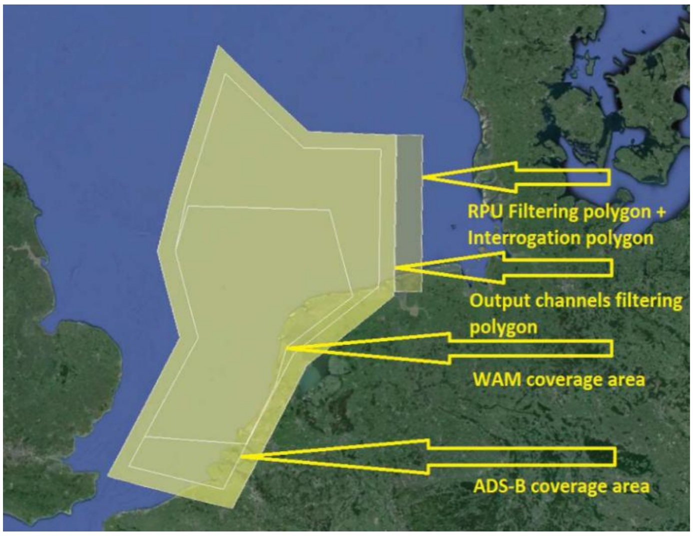

Figure 4: ADS-B Coverage Area (LVNL, 2024)

From the sensors the data is send in two times two data flows, through SURLAN-A and SURLAN-B. The central processing system consists of two Target Processors (TP) and two Management Systems (MS). Both the ADS-B and WAM data are sent to ARTAS-1, here the data is processed and together with radar data sent through Gateway to AAA. ARTAS is a air traffic management surveillance tracker and server, which is offered by EUROCONTROL (Eurocontrol, sd). AAA is the Amsterdam Advanced Air Traffic Control system, this is the system used for air traffic control in the Netherlands. Figure 5 contains a schematic overview of the data flow.

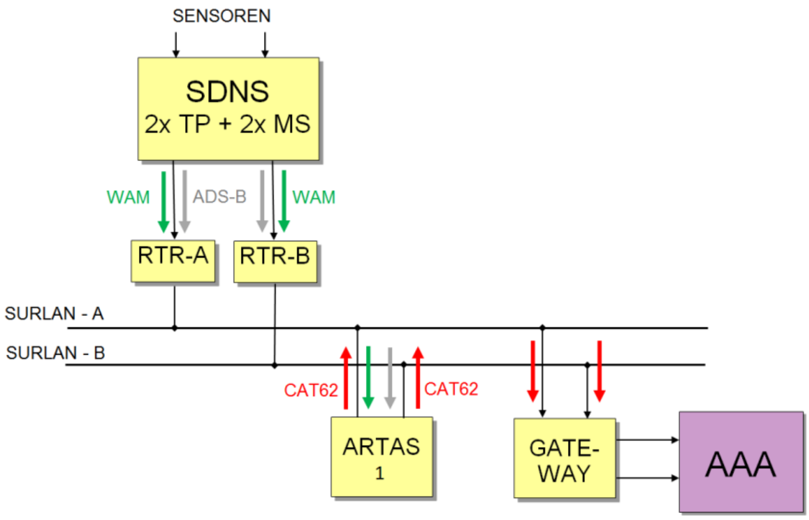

Figure 5: Schematic Overview of the Dataflow (LVNL, 2024)

3.3 Data Description

The data used was sourced from January 19th 2025 until May 11th 2025. This was all the available data at the time of retrieval. The data was stored in Comma-Separated Values (CSV) files, with each file containing 2 hours of a day, so a file for 00:00 to 02:00, from 02:00 to 04:00, etc. The first step was to combine the CSV files from one single day into one file. When this was done a column could be added to the data containing the date of that day. When each file also contained a column with the date, all the CSV files could be combined to one file, to make the analysis possible. Not all the columns in the dataset are needed for this thesis and some columns only consisted of NaN (Not a Number) values. To make the dataset more accessible to work with, several columns that were not needed have been removed. That leaves the dataset with the following information:

[ID]
The ID column contains the flight ID, this is a unique number assigned to a flight. The flight ID usually consists of two or three letters at the start, followed by two, three, or four numbers. An example of an flight ID is KLM856.

[FTIME]
The FTIME column shows the time at which de data was sent from the aircraft. It states the time following the format: HH:MM:SS.MS.

[Nur_Nav]
The Nur_Nav column contains the Navigation Accuracy Category for Velocity (NACv), this indicates the navigation accuracy for the velocity of the aircraft. NACv contains a value between 0 and 4.

[NUp_NIC]
This column contains the Navigation Integrity Category (NIC), this is a value between 0 and 11. As described in chapter 2, the higher the NIC category, the smaller the containment radios limit is.

[SIL]

The column SIL contains the Source Integrity Level, this is a subfield used to specify the probability of the true position lying outside the containment radius defined by NIC. SIL is a value between 0 and 3.

[Nap]
Nap is the column for Navigation Accuracy Category for Position (NACp), this indicates the accuracy of the position of the aircraft. NACp contains a value between 0 and 11, the higher the value the better the accuracy of the position.

[LAT]
The LAT column contains the latitude of the location of where the aircraft was when they sent out the data. Latitude is the position north or south of the equator and is measured from 0° to 90°. An example of a latitude could be 52.30. The dataset is bounded by the following lateral boundaries: lower limit 51.1335 N, upper limit 56.0699 N.

[LON]
The last column is the LON column, this contains the longitude of the location from where the aircraft sent out the data. Longitude is the position east or west of an imaginary line between the North and South Pole and is measured in degrees. An example of longitude is 4.76. The dataset is bounded by the following longitudinal boundaries: the Eastern boarder at 7.3 E, and the Western border at 1.6075 E.

[DATE]
The date column includes the date of when the messages were received. The date is in the format of day:month:year.

3.4 Data Analysis

With the collected data, trends, patterns, and relationships can be identified. The analysis focused on the distribution of the NIC and NAC values. A series of bar plots were generated to visualize the distribution of the NIC and NAC values. To get a clearer overview of the distribution between 'good' and 'bad' values, pie charts were used, based on the predefined thresholds for the NIC and NAC values. As well as a line plot to show the NIC values over the course of the time. This allowed for a quick visual assessment of the overall GNSS signal quality and the prevalence of anomalies.
In an effort to explore potential factors contributing to poor NIC values, several additional visualizations were created. A geographical map was plotted to assess whether spatial patterns or regional clustering were associated with lower NIC values. Other patterns that were investigated were categorical analyses performed to examine the relationship between NIC values and various contextual factors. These included the origin of the operators, as well as the classification of flights into commercial, military, and General Aviation (GA) categories. These breakdowns were visualized to determine whether specific operator groups or flight types were more commonly associated with poor NIC values.

3.4.1 Tools and Software

The data analysis was conducted using a combination of Python and Microsoft Excel. The raw data was stored in a CSV format, which allowed an easy integration into both tools. Python was used for the initial data inspection, combining of files, cleaning of the files, and creating all the visuals. Excel was mainly used to add additional information to the already existing dataset, such as the origin of the operators and their main purpose of aviation, e.g. commercial, General Aviation (GA), or military. This combination of software ensured the efficient handling of large dataset, while also being sufficient to make small changes.

3.5 Statistical Testing

To help avoid false claims and conclusions, hypothesis testing assesses the accuracy of a theory by testing it against data, it also helps to remove any biases (Majaski, 2024).
To complement the visual analysis and assess the significance of observed patterns, a statistical hypothesis testing was conducted.
For this hypothesis, suitable statistical tests were selected based on the data distribution and type of variables involved. The t-test was used to compare NIC values between two groups when assumptions of normality and homogeneity were met.

4. Results

In this chapter, the results and findings of this thesis are presented. In the first sub-chapter 4.1, the criteria for the thresholds are presented. By using these thresholds in combination with the data analysis, the results of the analysis can be found in sub-chapter 4.2. In this sub-chapter the quality of GNSS, the occurrence of bad GNSS quality, the correlations to bad GNSS quality can be found.

4.1 Criteria for the Thresholds

To be able to start the analysis of the GNSS signal quality, by using ADS-B data and looking at the NIC and NACp values, it is important to understand what is the international standard for the NIC and NAC values.

From 2015 to 2020, ICAO carried out a statistical analysis of surveillance data. On a monthly basis they compared RADAR and ADS-B data, demonstrating the evolution that the different versions and quality parameters of the ADS-B system has introduced over these years. This analysis shows that the predominant NIC value is NIC=8 and the predominant NAC value is NACp=9 (ICAO, 2022).

Besides ICAO the Federal Aviation Administration (FAA) §91.227 ADS-B out performance requirements requires the aircraft's NIC must be less than 0.2 nautical miles and the aircraft's NACp must be less than 0.05 nautical miles. This converts to a NIC value that must not be lower than 7 and a NACp value that must not be lower than 8 (FAA, 2023).

Furthermore, ICAO states that the transmission of a value of zero for both the NIC and NACp by an aircraft indicates a navigational uncertainty related to the position of the aircraft or a navigation integrity issue that is too significant to be used by air traffic controllers. If an aircraft operates within an Flight Information Region (FIR) where ADS-B based ATS surveillance service is provided and the aircraft ADS-B transmitting equipment becomes unserviceable resulting in the aircraft transmitting misleading information, then except when specifically authorized by the appropriate ATS authority, the aircraft shall not fly unless the equipment is either deactivated or transmits only a value of zero for the NIC or NACp.

In the problem categorisation they mention that aircraft transmitting incorrect positional data with NIC=0 should not be considered a safety problem. The data transmitted have no integrity and shall not be used by ATC. This situation exists for many aircraft when their GNSS receivers are not connected to the transponders. They state that there are two major approaches to manage the problems, one is regulations which require non-approved avionics to disable ADS-B transmission and the concerned operators to file flight plans to indicate no ADS-B equipage. The second way is the blacklist approach, by filtering out any airframes that do not comply with the regulations or are transmitting bad data (ICAO, 2022).

These international regulations from both ICAO and the FAA state that NIC values under 7 and NACp values under 8 are insufficient, therefore these will be the thresholds used for this thesis.

4.2 Result Data Analysis

With the acquired benchmarks the data analysis of the ADS-B data can start. This chapter will start with the general analysis of the GNSS signal quality, by analysing the NIC and NAC values, in sub-chapter 4.2.1. Then the occurrence of the bad GNSS quality will be covered in sub-chapter 4.2.2. To get a clearer insight in the possible correlations to bad GNSS signal quality, that could be made with the available data, sub-chapter 4.2.3 includes geographical location, operators aviation category, and operators Origins. Lastly to support the correlations, the hypothesis can be found in sub-chapter 4.2.4.

4.2.1 Quality of GNSS

The NIC values of the 4 months of data are displayed in figure 6, on the horizontal axis the NIC values from 0 to 11 are displayed. On the vertical axis it is displayed how many times the NIC values have been sent out. 5.8% is a NIC value of 7, 88.5% of the data contain a NIC value of 8, 3.6% has a value of 9, and 0.2% has a value of 10. All these values mean that the NIC can be considered good, but a NIC value of 6 or below, means a bad NIC value. In figure 7 the NIC values of below 7 are depicted. Here the big contribution of the NIC value of 0 can be found, with 0.517%, which is significantly higher than the other bad NIC values. As mentioned in chapter 4.1, ICAO states that NIC values of 0 do not have to be taken into account, but for full transparency of the data, this thesis will keep all the data points. When making the distinction between good and bad values, 1,8% of all NIC values fall into the bad category, as shown in figure 10.

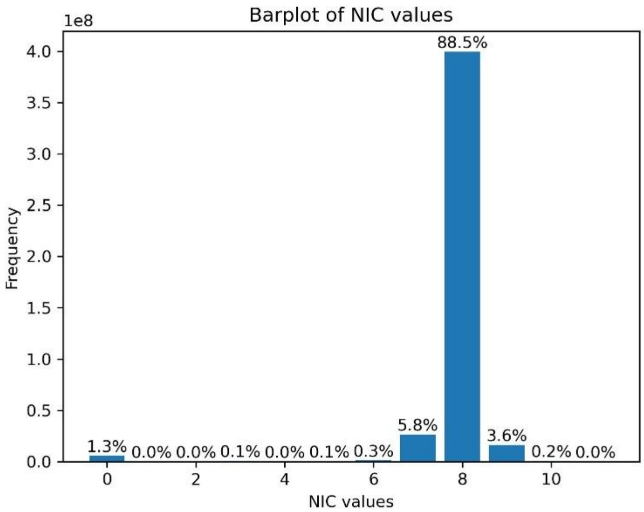

Figure 6: NIC Quality Distribution

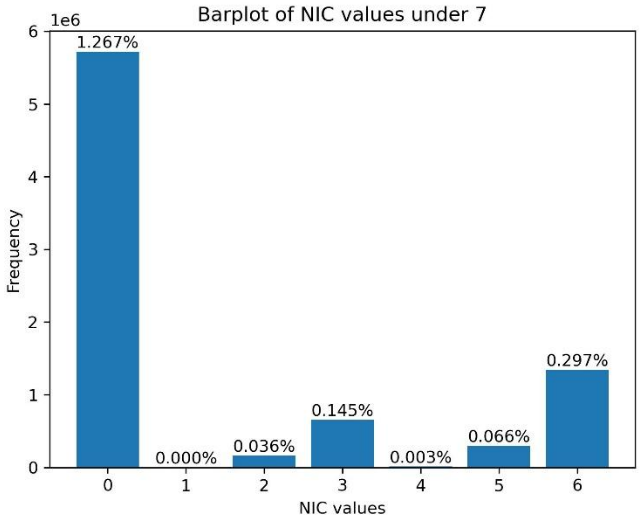

Figure 7: NIC Quality Distribution under 7

Figure 8 contains the distribution of the NACp values, these values are a bit more spread at the top than the NIC values. On the x-axis the NACp values are depicted, on the y-axis it is depicted how many times the NACp values have been sent out. 8.9% have a NACp value of 8, 48.2% a value of 9, 25.7% a value of 10, and 16.6% a value of 11. The bad, under 7, values of NACp are less divided then the NIC values, with only 0.6% of the values falling into the category, as shown in figure 11. Same as for the NIC values, the NACp values of 0 are still taken into account for this thesis.

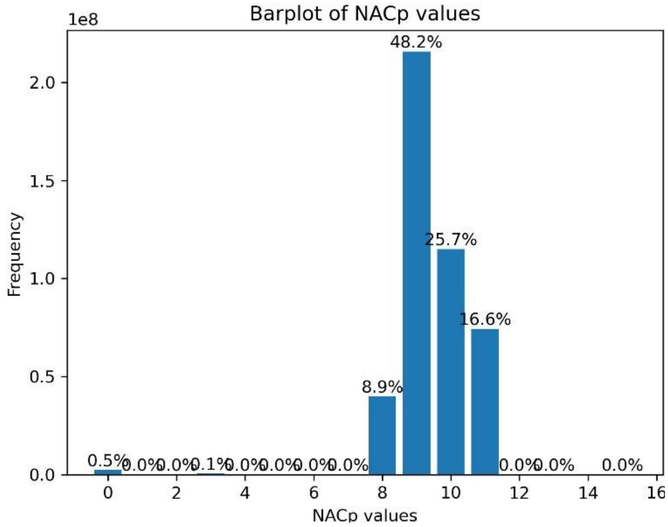

Figure 8: NACp Quality Distribution

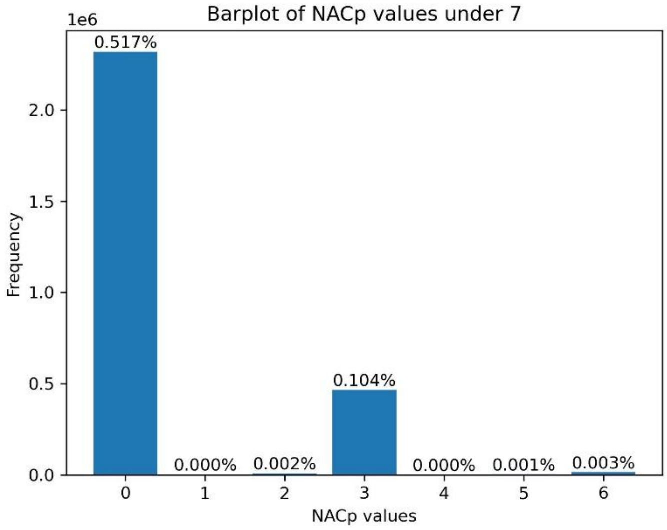

Figure 9: NACp Quality Distribution under 7

Given that NIC values shows a slightly broader distribution of lower quality data, they provide a more informative basis for further analysis. As such, the remainder of this study will focus on NIC values to ensure a more nuanced understanding of data quality across the dataset.

4.2.2 Occurrence of Bad GNSS Quality

To get a clear insight of the occurrence of bad GNSS quality the NIC values have been divided into two categories. The 'good NIC values' category are the NIC values of 7 or higher, the 'bad NIC values' are a 6 or below. The same has been done to the NAC values for comparison. In figure 10, it is shown that of all the sent out NIC values 1.8% fall into the bad category. For the NAC values this is only 0.6%, as shown in figure 11.

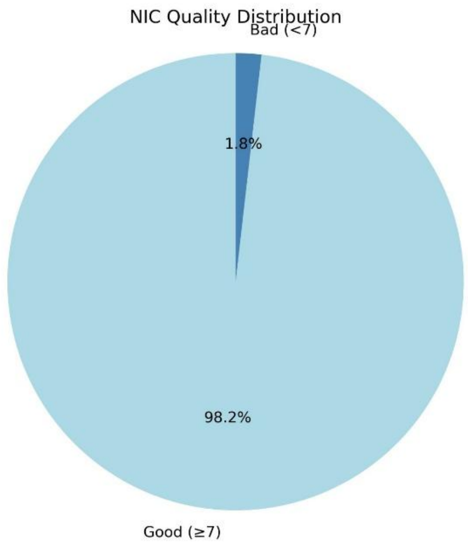

Figure 10: NIC Quality Distribution, Good and Bad

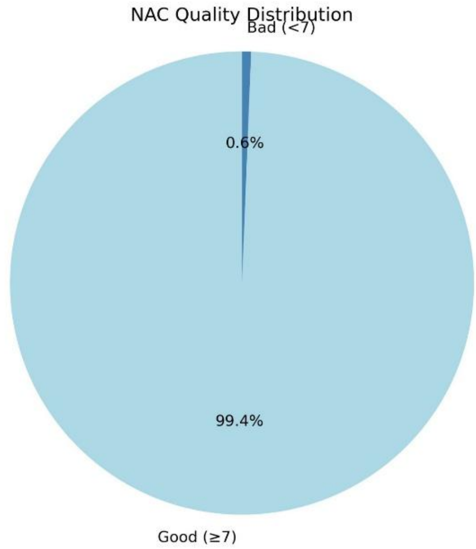

Figure 11: NAC Quality Distribution, Good and Bad

To get a better understanding if there is a correlation between the NIC values and the time of the year, the following graph has been made. In figure 12, the average NIC value per day can be seen. On the vertical axis the average NIC is displayed and on the horizontal axis the months are displayed. The graph shows that the NIC average per day, over the total of 4 months of derived data, is never less than 7.7 and never higher than 7.95. These averages therefore never fall into the bad NIC category. There is also no correlation between the months and the values, since the values fluctuate per day, but never remarkably high or low.

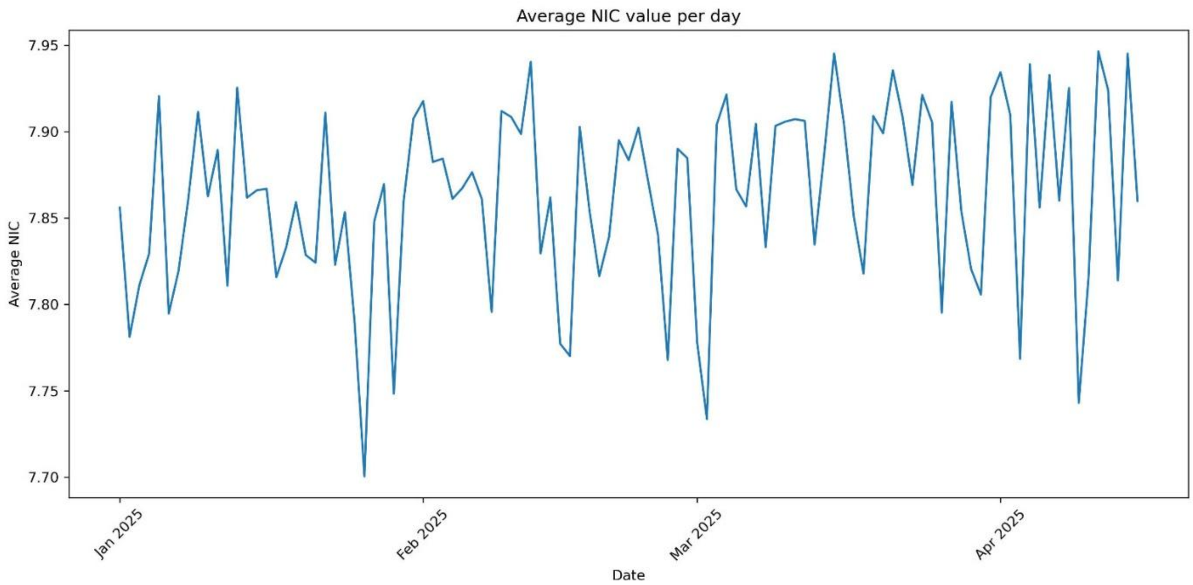

Figure 12: Average NIC Value per Day

4.2.3 Correlations to Bad GNSS Quality

The overall bad NIC values were only 1.8% of all the sent out values, but to get a better understanding of how these values came to be this chapter looks at any possible correlations to the bad GNSS signal quality. The first sub-chapter looks into the correlations of geographical location and the NIC values. The second sub-chapter looks at the operators aviation category. And lastly the operators origins have been taken under the loop. While the operators were not part of the original dataset, by looking at the flight ids, the operators could be traced and therefore also the aviation category and origin.

4.2.3.1 Geographical location

The first thing that is important to know is where in the Dutch Airspace the low NIC values are the most prevalent. To get an overview of the NIC distribution in the coverage area of the data, a map was created. The map was created with the latitude and longitude information of the dataset, the aera covered is divided into small hexagons, the lighter the hexagon, the better the NIC values are in that area. The darker the hexagons, the lower the NIC values in that area. The calculation made to determine the bad NIC rate is the amount of transmitted bad NIC values divided by the total amount of transmitted NIC value.

Because not all the data could be processed in the map, one day of each month was taken as a sample. Thus the map is made from the data of the dates 19-01-2025, 19-02-2025, 19-03-2025, 19-04-2025, and 11-05-2025. By picking one day for each month, the map depicts an average of the dataset, in Appendix A till Appendix E different maps can be found which use five days of each month, this shows that each month the same conflict areas arise and thus that this map is a clear depiction of the situation. The map can be seen in figure 13.

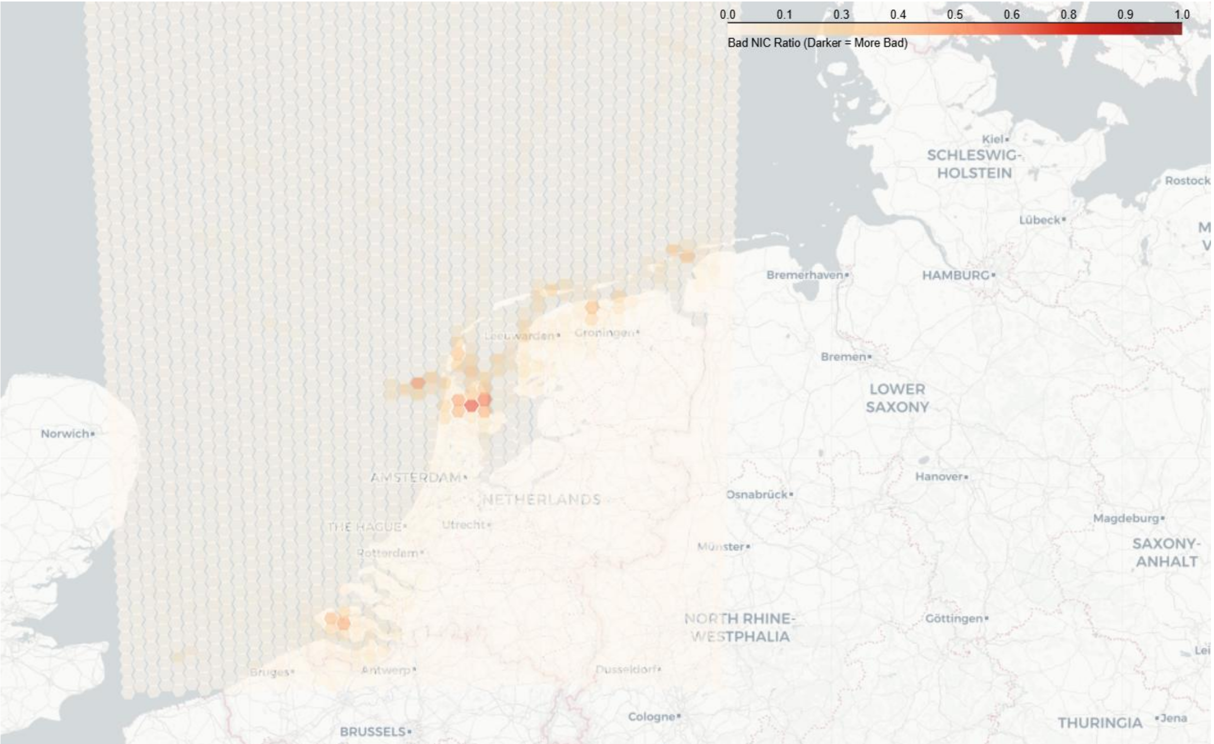

Figure 13: Geographical Map Showcasing the Bad NIC Ratio

The geographical map shows some darker hexagons around Northern Noord-Holland, the Waddeneilanden, and Zeeland. These are areas that are used a lot by recreational airplanes, but to reassure this, a list has been made of all the flight ids in areas where the bad ratio was above 0.4. To all the flight ids was then added whether they were commercial aviation or general aviation. In figure 14 below, the breakdown of the aviation types can be found. Here it shows that only 24% was commercial and that 76% was general aviation.

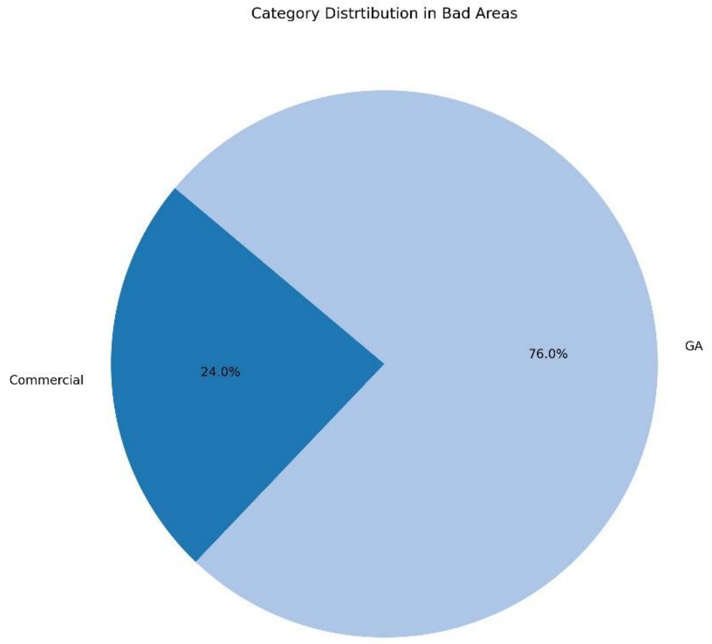

Figure 14: Category Distribution in Bad Areas

Shown in figure 15 is the distribution of good and bad NIC values for only general aviation, this showcases that general aviation admits a lot more bad signals than the overall 1.8%. Therefore we can say that there is no serious relation between geographical area and bad GNSS signals.

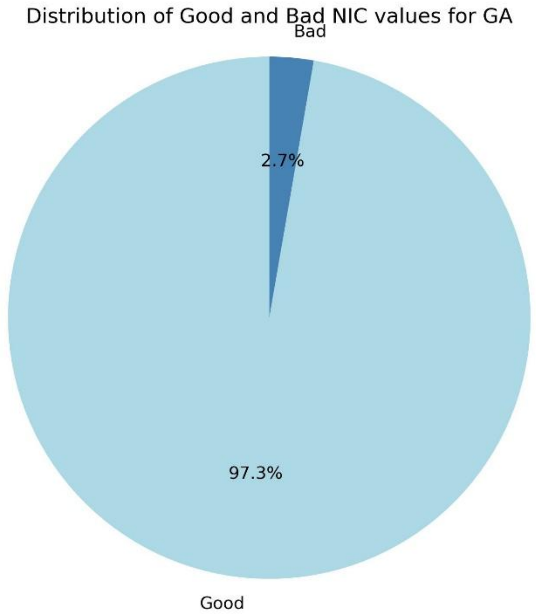

Figure 15: Distribution of Good and Bad NIC values for GA

4.2.3.2 Operators Aviation Category

To gain a clearer understanding of the aircraft that have transmitted this data, an analysis of the corresponding operators was conducted. As illustrated in figure 16, the majority of these operators fall under the commercial aviation category, accounting for approximately 87.8% of the total. General aviation represents the second largest group with 10.5%. The remaining share is distributed between military and aerial work, each contributing a relatively small portion to the overall dataset.

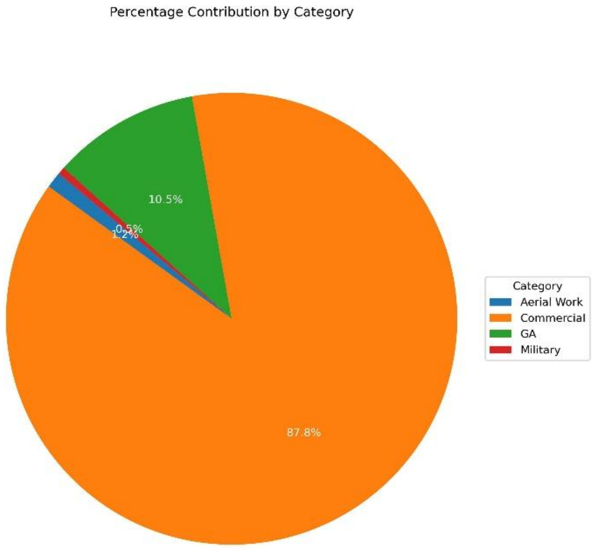

Figure 16: Percentage Contribution per Aviation Category

To better understand which operator categories contribute most significantly to poor NIC values, defined as values of 7 or below, figure 17 presents the distribution of these low-quality signals across the different categories. The data reveals that commercial aviation is responsible for 72.8% of all low NIC values, while general aviation accounts for the remaining share. Notably, contributions from military and aerial work operations are minimal, indicating that these sectors have a negligible impact on the overall volume of poor NIC values.

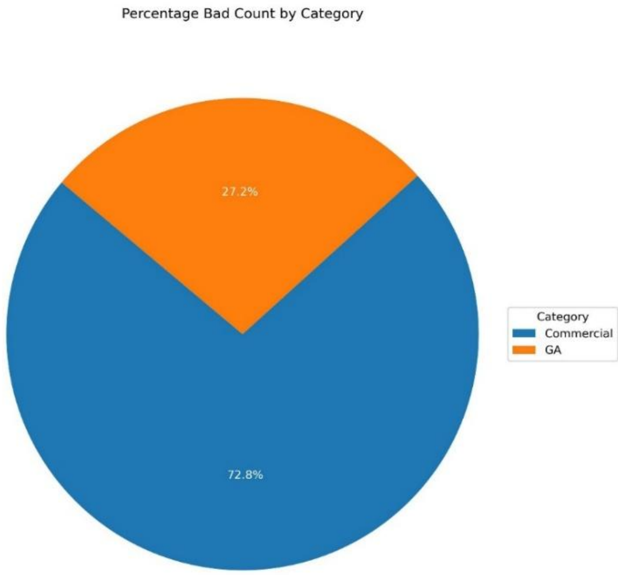

Figure 17: Percentage Bad NIC Count per Aviation Category

4.2.3.3 Operators Origins

In addition to categorizing operators by aviation type, their geographic origins have also been incorporated into the dataset. This allows for a deeper analysis of potential correlations between an operator's region of origin and the quality of NIC values.

Figure 18 presents a breakdown of the regional distribution of operators. As expected, the majority are based in Europe, accounting for 86.3% of the total, an unsurprising result given that the data collection as conducted within European airspace. The second largest group is made up of Asian operators at 6.4%, followed by operators from the Americas at 4.6%. Additionally, 2% of the operators originate from countries that span both Europe and Asia. A small number of operators from Africa and Oceania contribute the remaining portion of the dataset.

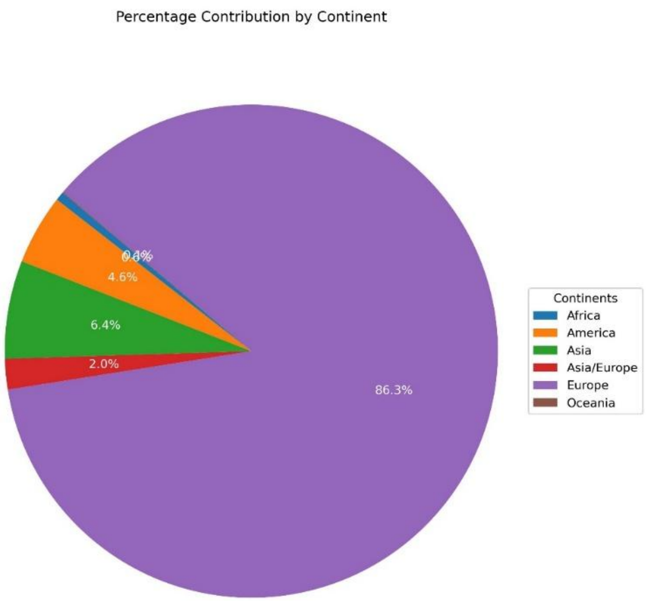

Figure 18: Percentage Contribution per Continent

To further contextualize the NIC values below 7, a breakdown by continent has been conducted, offering insight into which regions are the primary sources of poor NIC performance. As illustrated in figure 19, European operators account for the largest share of low NIC values at 67.1%. This aligns with the overall operator distribution presented earlier, where Europe dominated the dataset due to the location of data collection. A striking contrast appears when examining the contribution of Asian

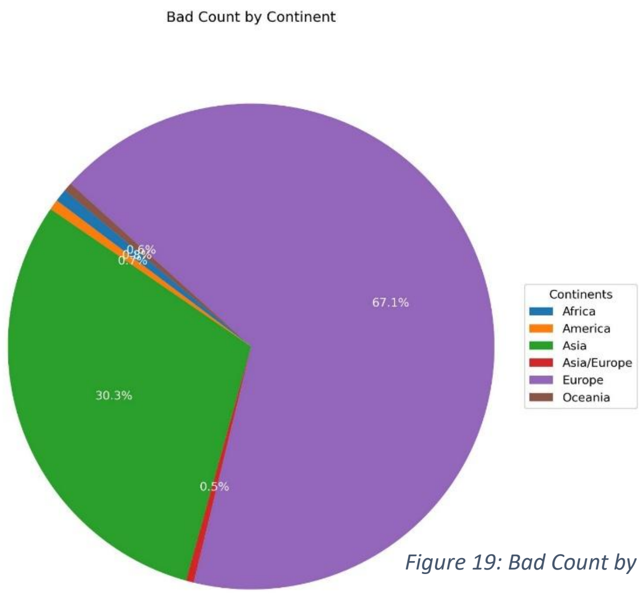

Figure 19: Bad Count by Continent

operators. Although they constitute only 6.4% of the total operator pool, they are responsible for a disproportionately high 30.3% of poor NIC values. This suggests that, relative to their representation, Asian operators contribute significantly more to degraded NIC performance. In contrast, operators from the Americas, Africa, and Oceania each account for less than 1% of the low NIC values, reflecting both their limited presence in the dataset and minimal impact on overall NIC degradation.

To combine the two previous observations, the final pie chart, shown in figure 17, presents the distribution of all poor NIC values across continents, but limited to commercial aviation only. Here, it can be seen that Europe remains the largest contributor, accounting for 54.9% of the poor NIC values. Asia is still the second largest contributor, now representing 41.6% of all low NIC values within this category. The other continents each remain around or below the 1% mark.

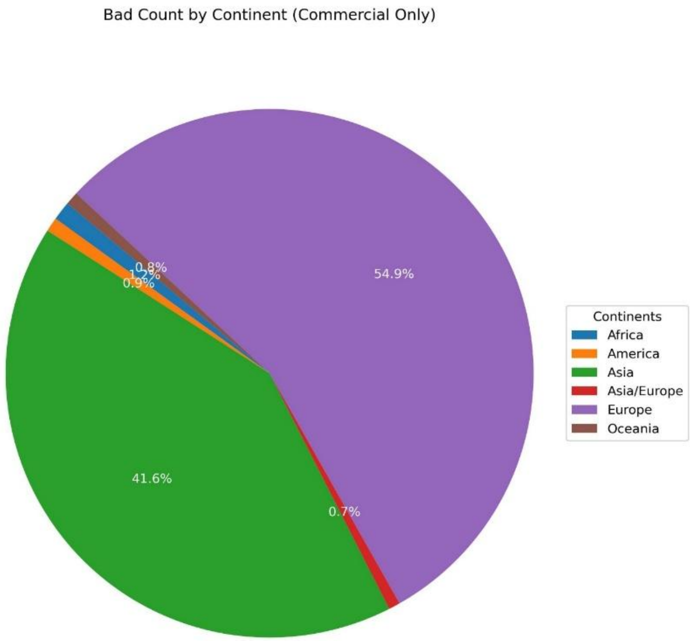

Figure 20: Bad Count by Continent (Commercial Only)

The previous graphs focused solely on the distribution of poor NIC values, without considering the presence of good NIC values, defined as scores of 7 or higher. In figure 21, the comparison between good and bad NIC values across continents is presented by calculating the percentage of bad values. The graph displays continents along the horizontal axis and the percentage of bad NIC values on the vertical axis. A red dotted line marks the global average of bad NIC values at 1.8%, as previously shown in figure 10. The weighted percentages reveal one major outlier: Oceania, with nearly 12% bad NIC values. However, it's important to note that this figure is based on data from only two operators in Oceania. In contrast, the dataset includes 58 operators from Asia, 1,616 from Europe, 10 from Africa, 56 from the Americas, and 63 from the Asia/Europe region. Asia has the second highest percentage of bad NIC values at 5.2%, while all other continents fall below the global average.

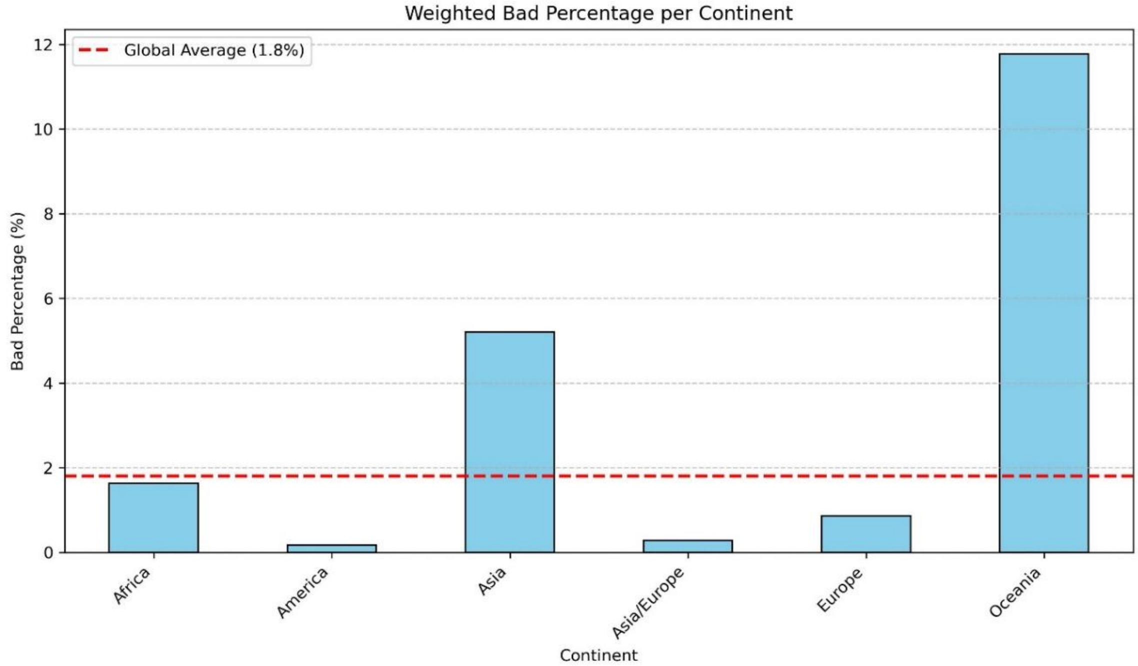

Figure 21: Weighted Bad Percentage per Continent

To make one final adjustment, this time focusing exclusively on commercial aviation, figure 22 was created. The results show minimal changes compared to previous figures. The most notable difference is that Europe's percentage of bad NIC values decreased slightly, from 0.9% to 0.6%.

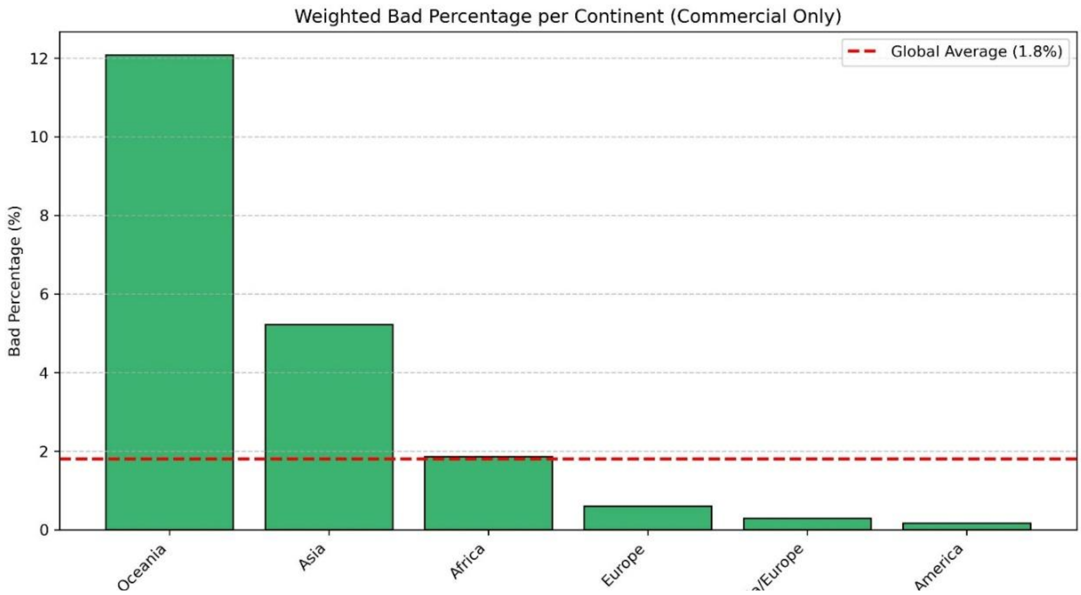

Figure 22: Weighted Bad Percentage per Continent (Commercial Only)

4.2.4 Hypothesis

The previous graphs showed a trend in the correlation of airlines who originate in Asia and the percentage of bad NIC values. To address this, the current chapter introduces a hypothesis specifically designed to validate the earlier findings.

The null hypothesis is:

H_0: Asian operators tend to have more bad NIC counts.

And the alternative hypothesis:

H_1:No significant evidence that Asian operators have more bad NIC counts.

If $p\text{-val} < 0.05$ H_0 is rejected, this means that there is evidence that Asia based airlines have higher bad NIC percentages. If p-val is ≥ 0.05 the outcome is fail to reject H_0, meaning that there is no strong evidence of a higher rate of low NIC values. The hypotheses is conducted by using a t-test, the t-test is perfect for comparing to variables, the bad percentage in this case, between two independent groups. For this hypothesis the two independent groups are operators from Asia and operators from other continents.

The outcome of this hypothesis was a p-val value of 0.0008 This means that p-val is smaller than alpha, therefore the null hypothesis is rejected, thus Asian operators tend to have more bad NIC counts.

5. Conclusion

The tragic crash of the Azerbaijan Airlines flight on Christmas Day 2024 underscores the critical importance of reliable GNSS in modern aviation. As aircraft increasingly depend on satellite-based navigation and surveillance systems like GPS and ADS-B, the growing threat of signal interference, particularly jamming and spoofing, poses a serious risk to flight safety. The vulnerability of GNSS signals, due to their low power and susceptibility to manipulation, highlights the urgent need for robust monitoring and mitigation strategies.

Automatic Dependent Surveillance–Broadcast (ADS-B) is a key technology that depends on GNSS to determine and broadcast aircraft position and other flight data. Parameters like Navigation Integrity Category (NIC) and Navigation Accuracy Category (NACp and NACv) within ADS-B data provide critical indicators of GNSS signal quality. Decreases in these values can signal potential GNSS disruptions, making them essential tools for monitoring and maintaining aviation safety. Understanding and analysing these parameters is crucial for detecting GNSS anomalies and ensuring the continued reliability of satellite-based navigation in increasingly complex and contested airspace environments.

Regulatory thresholds, NIC ≥ 7 and NACp ≥ 8, serve as essential benchmarks to ensure that aircraft are transmitting trustworthy positional data. When these values fall below acceptable limits, the data is deemed unreliable. The analysis of NIC and NACp values over a four-month period reveals that the vast majority of ADS-B transmissions in the dataset meet acceptable standards for navigation integrity and accuracy. Specifically, 88.5% of NIC values were 8, and 93.4% of NACp values were 9 or higher, both well above the regulatory thresholds. However, a small portion of the data, 1.8% for NIC and 0.6% for NACp, falls below the acceptable limits, indicating potential issues with GNSS signal quality. Given the broader distribution and slightly higher occurrence of low-quality values in NIC compared to NACp, NIC is selected as the primary focus for further analysis. This choice supports a more detailed and informative investigation into GNSS signal reliability within the dataset.

The geographical analysis of NIC values across Dutch airspace reveals that areas with higher occurrences of low NIC values, such as Northern Noord-Holland, the Waddeneilanden, and Zeeland, are predominantly associated with general aviation activity. Although these regions show elevated bad NIC ratios, further breakdown indicates that 76% of the flights in these zones are general aviation, which contributes disproportionately to the transmission of poor quality GNSS signals. Consequently, the data suggests that the prevalence of low NIC values is more strongly correlated with the type of aviation rather than specific geographic locations. Therefore, there is no significant geographical dependency in the occurrence of bad GNSS signals across the Netherlands.

The analysis of operator categories reveals that commercial aviation is the dominant contributor, accounting for 87.8% of all data, followed by general aviation at 10.5%. When focusing specifically on poor NIC values (≤7), commercial aviation remains the primary source, responsible for 72.8% of these low-quality signals. General aviation accounts for the remainder, while military and aerial work operations contribute minimally. Incorporating the geographic origin of operators into the analysis provides valuable insight into regional patterns of GNSS signal quality. While European operators dominate the dataset due to the location of data collection, they also account for the majority of poor NIC values, though proportionally, their performance remains relatively strong. In contrast, Asian operators, despite representing only 6.4% of the total, contribute disproportionately to degraded NIC values, making up over 30% of all poor NIC transmissions. This trend persists even when focusing exclusively on commercial aviation, where Asia accounts for 41.6% of poor NIC values compared to Europe’s 54.9%.

These findings suggest that while the volume of poor NIC values is highest among European operators due to their prevalence, the relative performance of Asian operators indicates a higher rate of GNSS signal degradation. When looking at the percentage of bad values that operators from each continent transmitted, both Oceania and Asia fall above the average of 1,8% bad values. While operators from Oceania are only 2 in the whole data set, this leaves Asia as the continent with the highest percentage of bad NIC values.

To validate the observed trend of higher rates of poor NIC values among Asian operators, a statistical hypothesis test was conducted. Using a two-sample t-test to compare the percentage of bad NIC values between Asian operators and those from other regions, the analysis yielded a p-value of 0.0008. Since this value is well below the significance threshold of 0.05, the null hypothesis is rejected. This provides strong statistical evidence that operators based in Asia tend to transmit a significantly higher proportion of low NIC values compared to operators from other continents. These findings reinforce earlier observations and highlight a regional disparity in GNSS signal quality.

One of the reasons for the Asian operators to get higher bad percentage could be due to the route that they fly. An assumption could be made that Asian operators that fly in Europe always fly to or from Asia. The route from Western Europe, where the data was collected, to any part of Asia, almost always passes a conflict zone. This could be in Eastern Europe or the Middle East. Another reason for a certain operator to have higher bad NIC values, could be due to the age of the fleet, with older aircraft come older systems, that could possibly lead to worse NIC values. Both of this assumption and other causes warrant further research.

6. Recommendations

The results of the analysis demonstrate Asian operators have a higher bad NIC count than operators from other continents, with the data derived in Western Europe. To get behind the reason why operators from Asian descent have this amount of bad NIC values, further research needs to be done. The first step would be to obtain better quality ADS-B data. The data used for this thesis did not include the departure and arrival location of each flight, and also did not include the aircraft type, while this should be available in ADS-B data. With this included in the data, more correlations can be found, e.g. flights from certain locations experience worse NIC values or looking at the route the flights have taken and if they flew over any conflict zones. Another correlation to bad NIC values could be the age of the aircraft, if the aircraft types are included in the dataset, more conclusions can be drawn to the influence of aircraft type and age to the NIC values.

Secondly, when this new ADS-B data is obtained, a live dashboard can be made to keep up to date to the newest development of GNSS quality in the airspace. This thesis did not conclude any correlations between geographical area and bad NIC values or time of day and bad NIC values, in the data derived from January 19th to May 11th, but in the current geo political state this is always subject to change. By creating a live dashboard, any changes in the GNSS quality, possibly due to jamming and spoofing, can be detected early so that repercussions can be in advance.

Together, these directions offer a path toward a more comprehensive and dynamic understanding of the GNSS signal quality in the Dutch airspace, contributing to both academic research and practical applications in airspace security.

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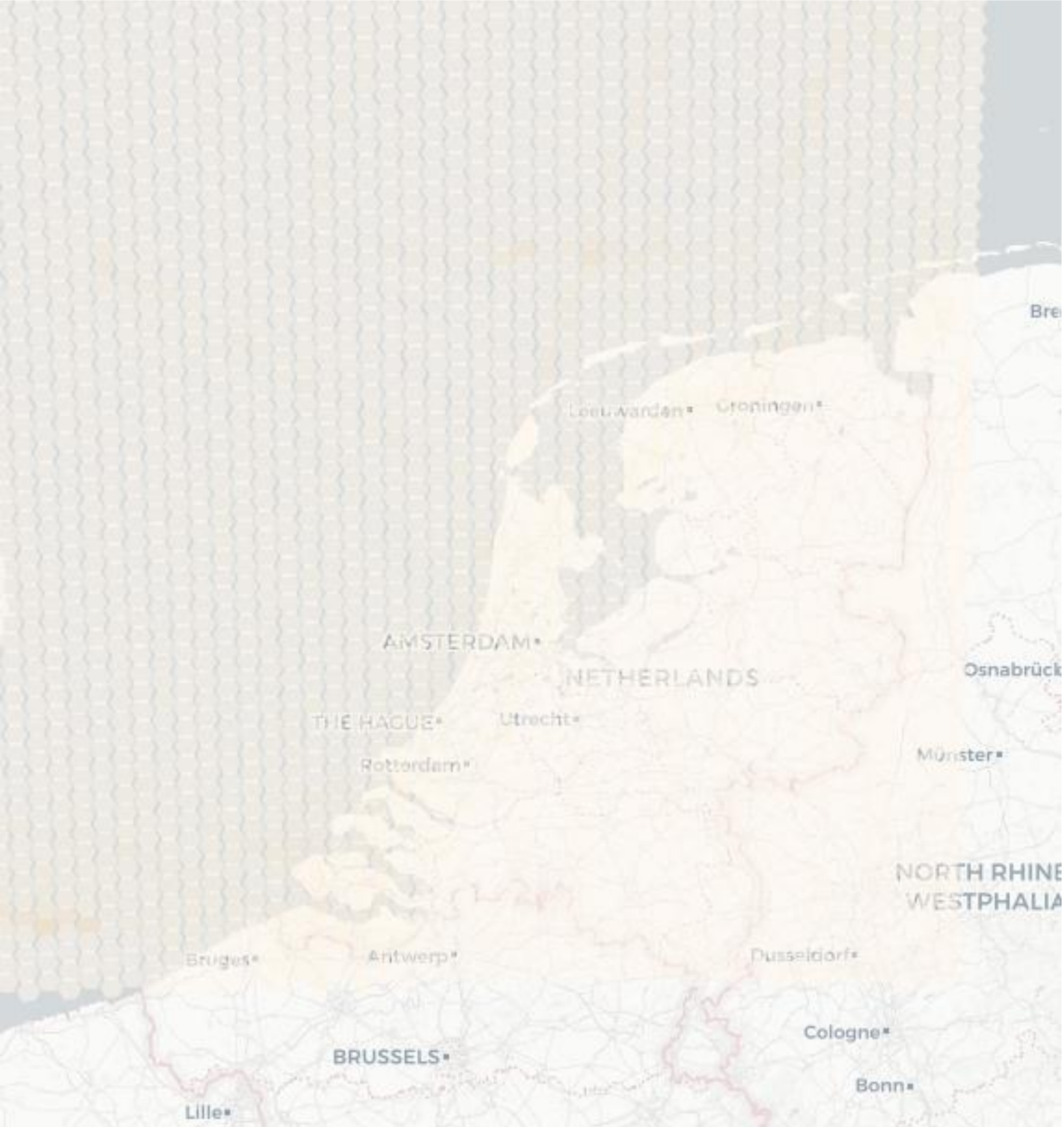
Appendices

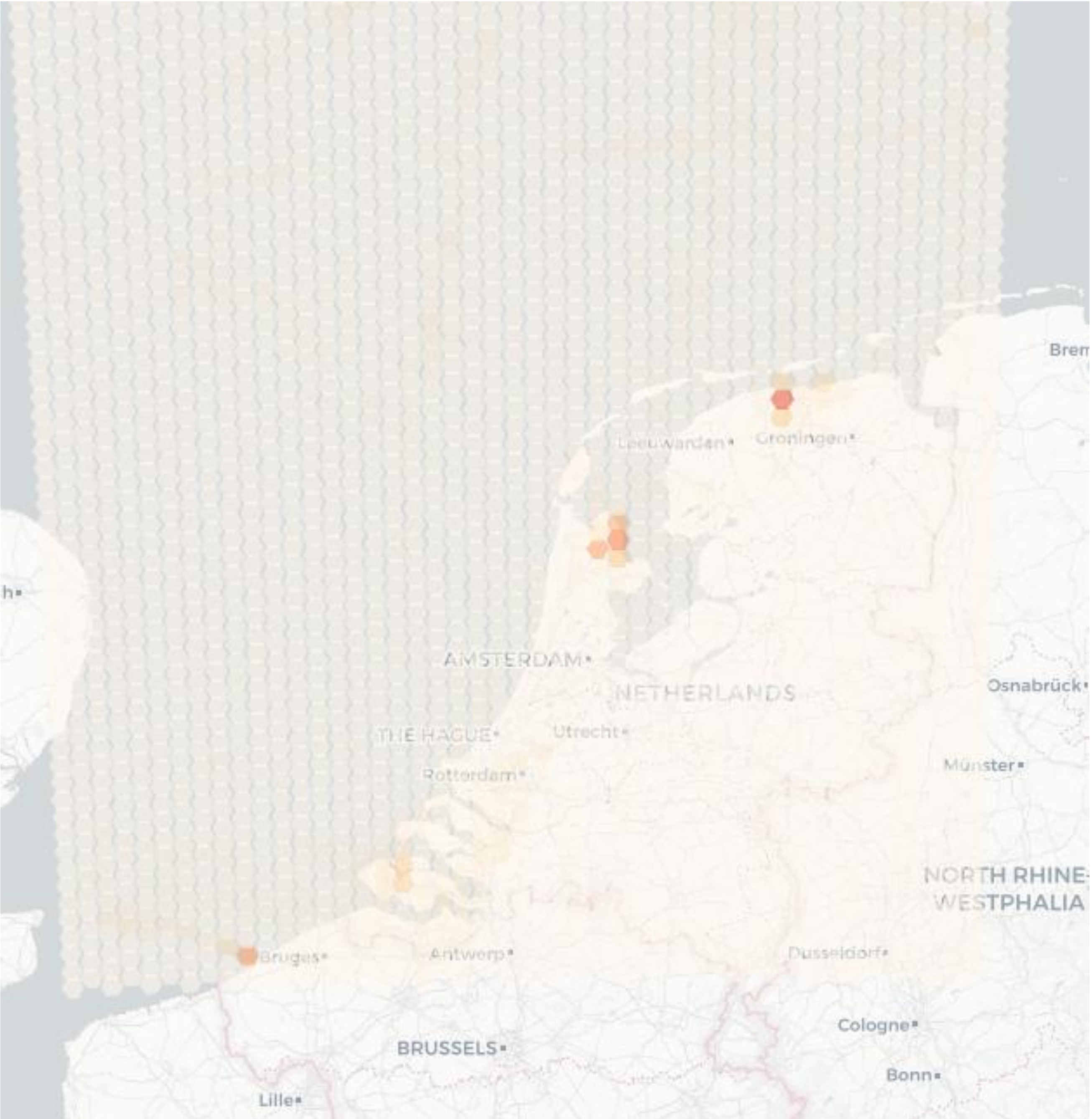
Appendix A

NIC ratio map of January, using the dates 19-01-2025 to 24-01-2025.



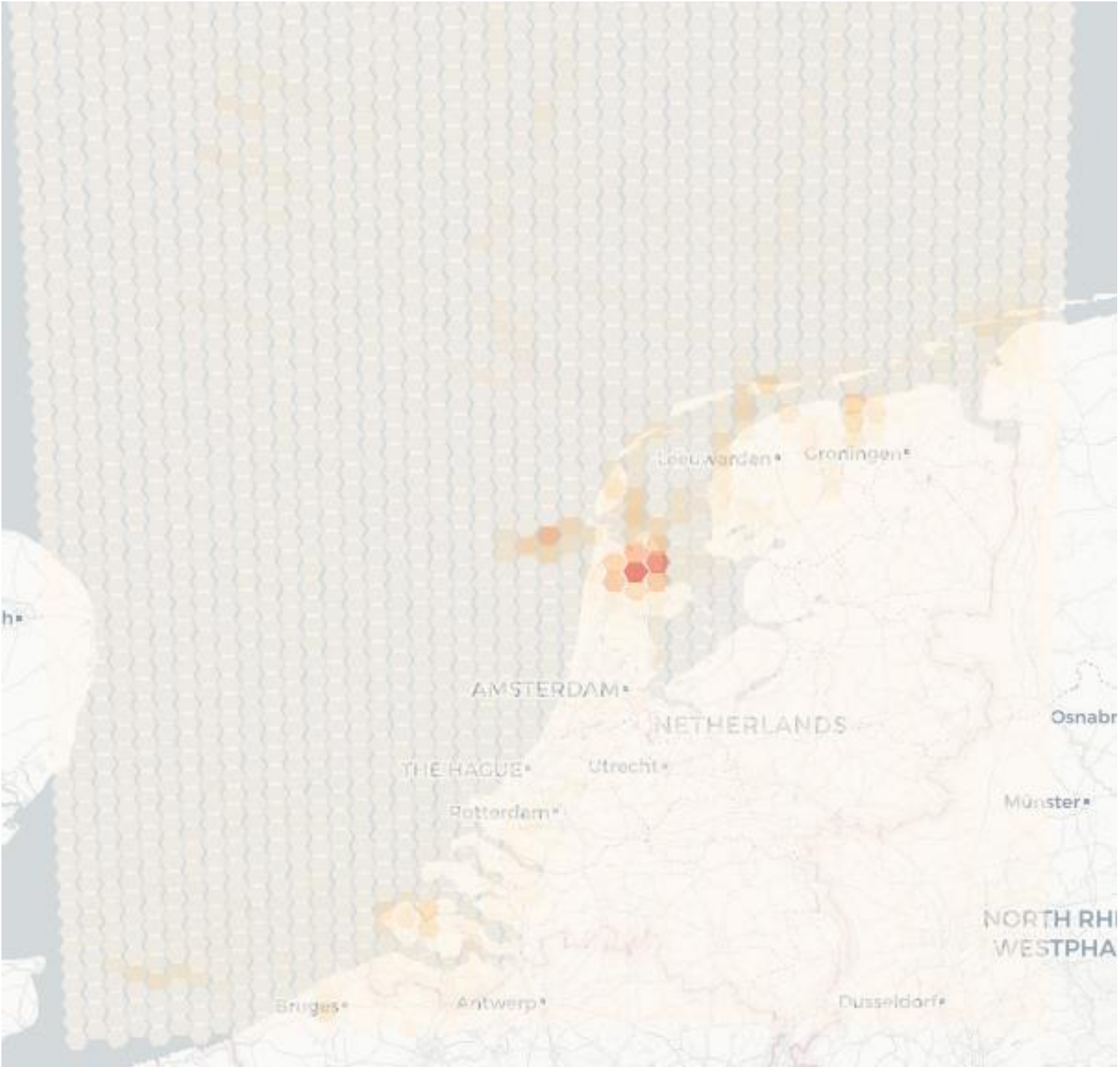
Appendix B

NIC ratio map of February, using the dates 19-02-2025 to 24-02-2025



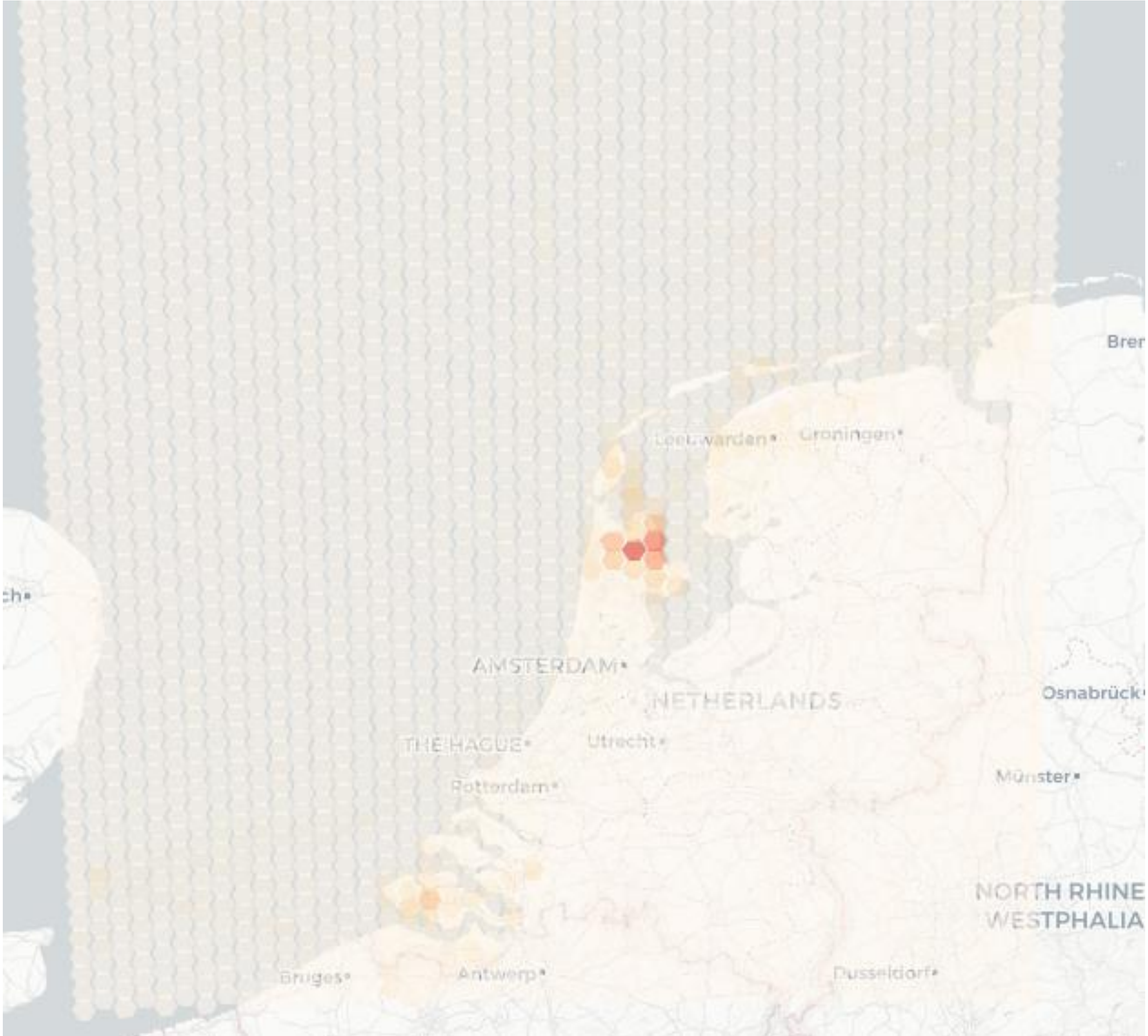
Appendix C

NIC ratio map of March, using the dates 19-03-2025 to 24-03-2025



Appendix D

NIC ratio map of April, using the dates 19-04-2025 to 24-04-2025



Appendix E

NIC ratio map of May, using the dates 07-05-2025 to 12-05-2025