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Effectiveness of a Bowtie-defined Safety Barrier Against GPS Spoofing in Regional Airline Operation

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ABSTRACT:

Global Navigation Satellite System (GNSS) interference, particularly GPS spoofing, has increased sharply in recent years, creating significant operational and safety challenges for airline operations. Procedural barriers in aviation rely on human recognition, interpretation, and decision-making, leaving their real-world effectiveness uncertain. This thesis evaluates the effectiveness of a Bowtie-defined procedural safety barrier “GPS navigation disabled in critical airspaces”, implemented by Nordic Regional Airlines (Norra) to mitigate spoofing-related risks. It uses a mixed-methods research design, combining deductive thematic analysis of semi-structured interviews with eleven ATR pilots and quantitative examination of 807 GNSS-related safety reports from 2022 to 2026.

Based on the four key attributes of functionality/effectiveness, reliability/availability, response time and human performance, discovered through literature review, the findings show that the barrier can be highly effective when used proactively. Pilots reported that deselecting GPS before entering known areas of interference prevents nearly all adverse navigation effects. However, its practical performance is strongly influenced by operational realities. Human factors emerged as the primary source of degradation with habituation to constant interference, normalization of deviance, and memory-dependent activation, but also serves as a key contributor to system reliance, providing adaptive experience-based actions to strengthen the overall safety during spoofing events.

Quantitative indicators, including newly developed Barrier Effectiveness Index (BEI), confirmed a dynamic risk environment. Spoofing exposure increased in distinct waves, with early months showing high escalation rates up to 90 percentage of spoofing events requiring ATC vectoring, while later periods showed reduced escalation, suggesting crew adaption and enhanced procedural familiarity. A fleet-level comparison further revealed that proactive GPS deselection in Embraer fleet produced more stable outcomes than reactive application in ATR fleet.

The study concludes that while the barrier is highly effective in principle, its real-world performance varies significantly due to human factors and operational constraints. Organizational recommendations include strengthening training to counter habituation, clarifying activation criteria, reducing reliance on memory, and enhancing data-driven barrier monitoring using KPI and AI-supported tools. The results highlight the need for dynamic, context-sensitive barrier management in aviation safety systems as GNSS interference continues to evolve.

KEYWORDS: Risk management, Interferences, Satellite navigation, Barriers, Aviation

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ABSTRACT:

Globaalin satelliittinavigointijärjestelmän (GNSS) häiriöitä, erityisesti GPS:n huijaamista, on viime vuosina havaittu merkittävästi aiempaa enemmän, muodostaen huomattavia operatiivisia- sekä turvallisuushaasteita lentoyhtiötoiminnalle. Ilmailun proseduraaliset suojaukset perustuvat usein henkilöstön havaintoon, tulkintaan sekä päätöksentekoon, lisäten epävarmuutta niiden todellisesta tehokkuudesta operatiivisessa ympäristössä. Nordic Regional Airlines (Norra) on implementoinut Bowtie-malliin perustuvan proseduraalisen suojauksen ”GPS-navigointi pois käytöstä kriittisissä ilmatiloissa”, jota tässä työssä tarkastellaan GPS:n huijaamisen hallinnan näkökulmasta. Työssä on sovellettu monimenetelmällistä tutkimusstrategiaa, jossa on yhdistetty deduktiivinen temaattinen analyysi yhdestätoista ATR-lentäjälle tehdystä haastattelusta sekä 807 GNSS-häiriöihin liittyvän turvallisuusraportin kvantitatiivinen tarkastelu vuosilta 2022-2026.

Kirjallisuuskatsauksessa on tunnistettu neljä keskeistä suorituskykyattribuuttia: toimivuus/vaikuttavuus, luotettavuus/saatavuus, vasteaika ja inhimillinen suoriutuminen. Näiden neljän attribuutin perusteella on havaittu, että suojaus voi olla erittäin tehokas, kun sitä käytetään ennakoivasti. Lentäjien mukaan GPS:n kytkeminen pois ennen tunnetuille häiriöalueille saapumista ehkäisee lähes kaikki navigointihaasteet. Käytännön toimivuutta on kuitenkin heikentänyt operatiivinen kuormitus sekä inhimilliset tekijät, kuten turtuminen jatkuviin häiriöihin, poikkeamien normalisoituminen ja muistinvarainen käyttöönotto. Samanaikaisesti lentäjien toiminta on kuitenkin tärkeä osa järjestelmän mukautumiskykyä, sillä se tuo tilanteisiin kokemukseen perustuvia sekä turvallisuutta vahvistavia toimintatapoja.

Kvantitatiiviset indikaattorit, mukaan lukien uusi Barrier Effectiveness Index (BEI), osoittavat riskin dynaamisen luonteen, jossa GPS:n huijaus todetaan esiintyvän aaltoilevina jaksoina. Varhaisessa vaiheessa jopa 90 prosenttia tapauksista johti lennonjohdolta tarvittavaan vektorointiin, kun taas myöhemmissä jaksoissa eskalaatio väheni, viitaten miehistöjen mahdolliseen sopeutumiseen ja kasvaneeseen menetelmätuntemukseen. Laivastotason vertailu osoitti myös, että GPS:n ennakoiva poiskytkentä Embraer-laivastossa johti huomattavasti vakaampiin lopputuloksiin kuin ATR-laivaston reaktiivinen toimintamalli.

Tulokset osoittavat, että vaikka suojaus on erittäin tehokas, sen todellinen suorituskyky vaihtelee merkittävästi inhimillisten tekijöiden ja operatiivisten rajoitteiden vuoksi. Organisaatiotason suosituksina esitetään koulutuksen vahvistamista häirintään tottumisen torjumiseksi, suojauksen aktivointikriteerien selkeyttämistä, muistiriippuvuuden vähentämistä sekä tietoperusteisen suojausvalvonnan kehittämistä KPI-mittareiden ja tekoälypohjaisten työkalujen avulla. Tulokset korostavat tarvetta dynaamiselle suojaushallinnalle osana turvallisuusjärjestelmiä GNSS-häiriöiden kehittyessä.

KEYWORDS: Risk management, Interferences, Satellite navigation, Barriers, Aviation

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Introduction

The introduction section consists of chapters background, aim of the study and research questions, structure and limitations, and case company. This section gives comprehensive overview of the the research, also determining the structure with the limitations due to the nature of it.

1.1 Background

Modern operations introduce multiple sources of operational risks for companies, arising from increasing complexity of the systems. To manage such risks, a bowtie method is often applied as part of the safety management system, being widely adopted in high-hazard industries such as gas, mining and aviation (de Ruijter & Guldenmund, 2015).

Existing literature largely focuses on identification and modelling of risks using bowtie diagrams or the practicality of these. The bowtie literature regarding the aviation business is however wide providing some confirmation that the bowtie method is useful in such industries. For example, Leitão et al. (2022) studied the usage of bowtie method in flight training creating own practical application of a bowtie for spin maneuver training, whereas study by Aust and Pons (2019) used bowtie to determine the hazards of aircraft part inspection. However, less attention has been paid on how bowtie-defined safety barriers perform after these have been implemented in everyday operations, particularly when the barriers are procedural rather than technical, in aviation operations.

De Rademaeker et al. (2013) noted, that in principle, technical, administrative, and procedural controls can be given realistic reliability or effectiveness targets. However, human and organizational factors may influence many barriers simultaneously, possibly leading to dependent failures. Therefore, procedural barriers in aviation, such as operational bulletins and guidance given by the airline operator, depend on human recognition, interpretation, and decision-making, leaving their real-world effectiveness uncertain. Hence, a research gap can be identified in understanding whether formally defined procedural safety barriers achieve their intended effect in practice and how their performance can be evaluated using operational data, especially within aviation where safety is the primary objective.

Research on GNSS (Global Navigation Satellite System) interference in aviation has predominantly adopted a technical or regulatory perspective, while empirical evaluations of organizational and procedural risk controls in this context remain limited. Globally GNSS interference has increased rapidly, impacting civil aviation in September 2023 starting with few flights affected, but by 2024 within one month observation period, total of 41 000 flights had experienced spoofing type of interference (OPSGROUP, 2024). In Finland similar trend has been seen with exponential increase in GNSS interference from 2022 to 2024 according to Traficom (Finnish Transport and Communications Agency) statistics (2024), leading airliners to struggle with delays, safety concerns, and increased costs as a consequence. To counteract these effects, airliners have adopted measures to maintain the reliability and safety of the navigation, often described using the bowtie method. Since GNSS interference offers a rich empirical basis due to the large number of reported events, this study therefore focuses on evaluating the effectiveness of a specific safety barrier using a mixed-method approach.

1.2 Aim of the study and research questions

The aim of this study is to evaluate the effectiveness of the case company’s bowtie-defined procedural safety barrier “*GPS navigation disabled in critical airspaces*”, implemented to mitigate GNSS related operational risks by deselecting GPS to maintain navigation integrity under suspected or known signal interference. While GPS related operational risks remain as the event, the study focuses mainly on organizational level analysis regarding the efficiency of the safety barrier, finding suggestions and reasons for it.

The research will be conducted using mixed method approach, and by thorough literature review. Through the literature review reader is familiarized with the common concepts related to bowties and its barriers, which are then used to formulate the main themes around the qualitative research. Furthermore, the section provides insights to the current challenges regarding the global GNSS interference. In the quantitative part, data provided by case company's reporting system is analyzed using artificial intelligence for word identification to form indicators to reveal potential patterns within the reports and eventually to form key performance indicator (KPI) of Barrier Effective Index (BEI). Qualitative data collection is based on the pilot interviews conducted using the semi-structured interviews and the main themes determined in the literature review, to compare the intended function of the barrier and its usage in operational field. Together with the empirical assessment of the operational effectiveness, the aim is to find practical recommendations for improving the barrier management and monitoring in organizational level.

The research problem is formulated based on the study's background and objectives, addressing the lack of clarity in how the effectiveness of procedural safety barriers is operationally evaluated and understood within the bowtie method. The study is guided by the following two research questions:

Research question 1: *How effective is a bowtie-defined procedural safety barrier in mitigating GPS spoofing related risks in regional airline operation?*

Research question 2: *What type of barrier performance modes can be identified from the safety reports and pilot interviews?*

The first research questions examine the effectiveness of the barrier in wider spectrum, focusing on spoofing type of interference, whereas the second research question intends to identify the performance modes, through which the barrier operates in practice. Together, these frame the study’s aim of understanding of not only how well the barrier works, but also how it behaves under operational conditions, seeking to build a holistic view of the barrier’s strengths, limitations, and human-contextual factors that shape its performance. The findings of the research intend to support improved decision-making in risk management, highlight limitations of procedural controls, and provide guidance for the effective use of bowtie-based safety models within the organization.

1.3 Structure and limitations

The research consists of five chapters, starting with *introduction*, including background of the study to support the objectives and research questions, along with structure and limitations, and case company introduction. The second chapter *literature review* handles topics of bowtie, organizational risk management, barrier performance, and GNSS as operational risk. The literature review chapter summarizes the existing literature regarding the topics to position the current research within the prior work, while also supporting the analyses, providing theoretical framework for the qualitative interviews. Third section, *Methods,* explains research design together with data sources and collection. The main data provided by case company’s safety reports from 2022 to 2026 and number of operations for each month. The data will be then analyzed together with the qualitative semi-structured interviews to form comprehensive overview of the barrier’s performance. *Results* section follows including the results from both qualitative semi-structured interviews and quantitative reporting data analysis. The qualitative chapter is divided into subsections according to the themes found in the literature review. Last chapter *conclusion* generalizes the results of the research, along with possibilities for future research.

The research is limited only to single-case design of one case company, while reliance on self-reported data within limited observation period. The focus is on procedural barrier leaving larger technical mitigations outside the scope of the analysis. Furthermore, the findings provide organizational specific insights into risk control performance rather than generalizable conclusion. As the thesis is intended for open publication, the details presented in the findings has been reviewed with the company to avoid the disclosure of organization-specific sensitive information.

1.4 Case company

Nordic Regional Airlines, or commonly referred as “Norra”, is a Finnish regional airline founded in 1993. Norra is owned as a joint venture by Danish Air Transport A/S (DAT) and Finnair, DAT being majority owner with 60% share and Finnair as minority shareholder with 40% share (Nordic Regional Airlines, n.d.). According to the company website, Norra operates a fleet of 24 aircrafts including 12 ATR 72-500’s and 12 Embraer 190’s with over 50 000 operations each year, which of over 3 million passengers are flown for Finnair. As of 2025 Norra is Finland’s second largest airline and Finnair’s strategic partner.

Operations of Norra include multiple European destinations. ATR aircrafts are used mainly to operate domestic routes along with destinations in the Nordic and Baltic countries, having in July 2025 26 different destinations in total for Finnair (Finnair, 2025). For Embraer, the routes are also mainly domestic and within the Nordic countries with some selected Central European routes, but at times deployed for longer routes such as Naples (Finnair, 2025a).

In the context of this research, Norra offers highly relevant operational insight into prevailing GNSS interference, as many of its most frequently operated routes traverse the primary interference areas identified in recent years. This makes the company especially suitable case for examining the effectiveness of the bowtie barrier. Furthermore, the company has been interested in finding new solutions to estimate the performance of the barriers laid down to mitigate the risks within the operational field, as the company growth and changing operational environment require this sort of flexibility. In addition, Norra’s established and comprehensive safety culture, with well documented data, provides a strong foundation for conduction organization-wide evaluation of the bowtie barrier’s effectiveness.

2 Literature review

This chapter reviews the theoretical foundations needed to analyze the effectiveness of a bowtie-defined procedural safety barrier for GPS spoofing in regional airline operations. It first introduces organizational and enterprise risk management, showing how safety and operational risk controls are embedded in wider management systems and, in aviation, through safety management system (SMS). These frameworks intend to clarify how procedural barriers are planned, governed, and monitored at organizational level, essential for understanding bowtie's location in real operations.

The chapter examines the bowtie method and the concept of safety barrier, including barrier types, performance attributes, and the role of human and organizational factors in barrier management. These concepts introduce the basic components of the method, providing clear structure for linking threats, barriers, and consequences, while performance and human factors determine whether the controls laid down work as intended in practice. Building on this, the chapter reviews literature on barrier performance assessment and dynamic barrier management, informing the study's approach to evaluating procedural barrier effectiveness using qualitative and quantitative methods.

Finally, the chapter introduces knowledge regarding GNSS generally and GNSS interference in civil aviation, with emphasis on Baltic and Finnish region, to position the study within the broader context of the operational region of GNSS-related risks, linking the general concepts within the study area, enhancing the practical relevance of the analysis.

2.1 Organizational risk management

Organization to manage risks effectively requires the implementation of solid risk management framework and practices (Fiorentini, 2021). ISO (International Organization for Standardization) defines ISO 31000 as standard for risk management, setting guidelines and principles for organizations to manage risks more efficiently (n.d.). Fiorentini (2021) describes that the eight principles for risk management laid down by ISO 31000 should be adhered by each organization at all levels to work effectively and efficiently. The eight principles are:

1st – "*Risk management is an integral part of all organizational activities*"
2nd – "*A structured and comprehensive approach to risk management contributes to consistent and comparable results*"
3rd – "*The risk management framework and process are customized and proportionate to the organization's external and internal context related to its objectives*"
4th – "*Appropriate and timely involvement of stakeholders enables their knowledge, views, and perceptions to be considered. This results in improved awareness and informed risk management*"
5th – *"Risk can emerge, change or disappear as an organization's external and internal context changes. Risk management participates, detects acknowledges and responds to those changes and events in an appropriate and timely manner "*
6th – *"The inputs to risk management are based on historical and current information, as well as on future expectations. Risk management explicitly takes into account any limitations and uncertainties associated with such information and expectations. Information should be timely, clear and available to relevant stakeholders"*
7th – "*Human behavior and culture significantly influence all aspects of risk management at each level and stage*"
8th – *"Risk management is continually improved through learning and experience"*

Building on these principles of risk management, more advanced risk management approach can be adopted, called Enterprise Risk Management (ERM), considering whole organizational wide practices, culture and skills, integrated with strategy and performance of the company (Fiorentini, 2021). According to Khan et al. (2016), ERM is defined as holistic approach to risk management that includes integrating all possible risks across the entire organization, and manages them collectively from a portfolio perspective, rather than addressing risks in isolation. This approach enables organizations to systematically identify, assess, and manage risks across the enterprise as a whole (Anton & Nucu, 2020). ERM is often structured based on five components to manage risk in line with organizations risk appetite and tolerance, offering reasonable assurance to management and support achieving the organizational objective across domains (Fiorentini, 2021). These five components are *governance and culture, strategy and objective, performance, review and revision,* and *information, communication and reporting.*

There are often multiple factors affecting the companies' decision to include ERM into the systems. Khan et al. (2016) describe these either as internal or external. The authors describe factors such as higher probability for financial distress, opportunities for growth, recent poor performance, and strong corporate governance as usual reasons to implement and initiate ERM internally, while external reasons for firms to implement ERM are usually due to local regulations. Furthermore, Fiorentini (2021) describes that four main business risks of *strategic, financial, compliance, and operational,* often drives companies towards ERM, and are considered in it.

In aviation business, risk management is highly needed across all organizational levels, due to the complexity of the systems. Flight operations process is a large ensemble, comprising of activities such as flight planning process, active flight operation, and safety and quality improvement process, according to Cahill et al. (2014). Flight planning process includes long and short-term planning, having three main phases: commercial flight planning, aircraft pairing and rostering, and dispatch (Cahill et al., 2014). Active flight operation is also divided into three main components of pre-flight, flight execution, and post flight, where cockpit usually consists of captain and first officer, divided into roles between pilot flying (PF) and pilot monitoring (PM) (Cahill et al., 2014). Captain is in command of the whole flight as well as responsible for approving the aircrafts airworthiness, while first officer is the second in command, but both pilots share responsibility for flying and navigating the aircraft (Cahill et al., 2014). Furthermore, the active flight operation phase includes multiple other operational teams, such as cabin crew and air traffic control (ATC). All of the main phases of flight operation include various subphases that are visualized in Figure 1.

Safety and quality improvement process is also highly connected to the active flight phase, as crew reporting has an important role in providing feedback of the events, as this is used for identification and understanding of potential threats and to improve the performance of the processes, but also connects and runs different functions of the organization, such as training and safety (Cahill et al., 2014).

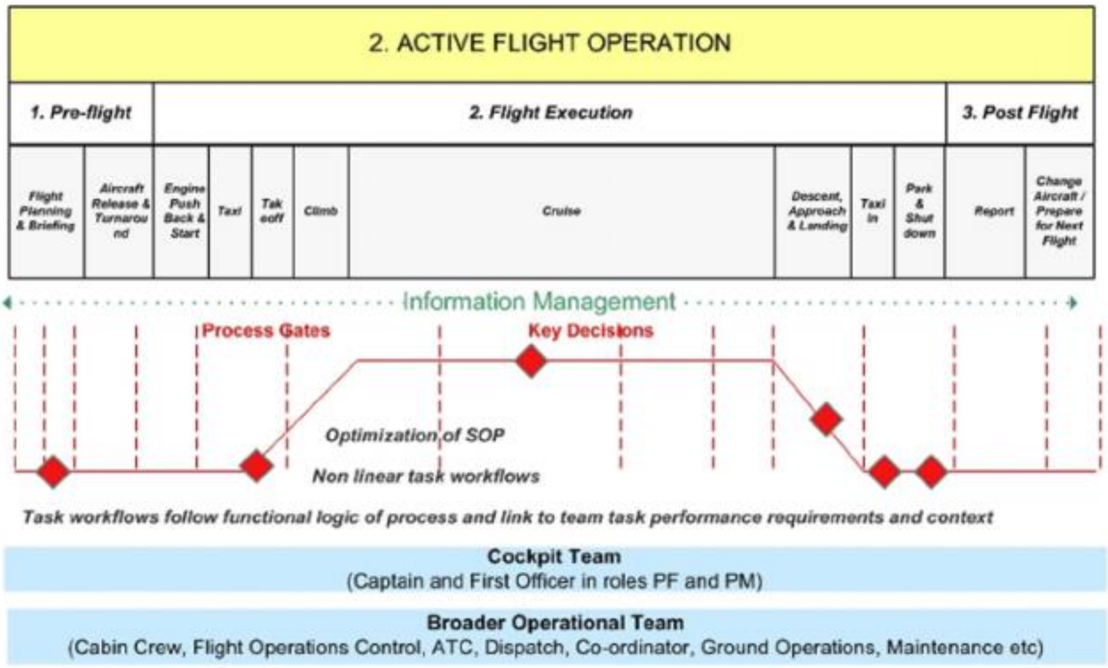


Figure 1. Flight Crew Task and Active Flight Operations process (Cahill et al., 2014)

To compensate the complexity of the operations, aviation regulators such as EASA (European Union Aviation Safety Agency) and FAA (Federal Aviation Administration) have implemented mandatory requirements of Safety Management System (SMS) for organizations involved in commercial aviation to obtain, in order to perform operations and activities (Cacciabue et al., 2015).

The FAA (2024) introduces SMS as: "…the formal, top-down, organization-wide approach to managing safety risk and assuring the effectiveness of safety risk controls…" and "…includes systematic procedures, practices, and polices for the management of safety risk.". EASA implements SMS within the management system framework, which addresses the basic factors included within the ICAO (international Civil Aviation Organization) SMS, while still supporting a coordinated, organization-wide approach to management (European Union Aviation Safety Agency, n.d.). EASA doesn't encourage organizations to impose fully new system, but rather to facilitate additional safety management components to be built upon the existing management system. In management system framework, EASA (n.d.) however mandates organizations to comply e.g. with the following:

- Implement an occurrence reporting system that meets the requirements defined in Regulation (EU) No 376/2014
- Implement internal safety reporting procedures in line with 'just culture' principles
- Ensure the identification of aviation safety hazards posed by its activities, ensure their evaluation, and management of associated risks, including:
    - taking action to mitigate the risks, and
    - verifying the effectiveness of each action taken to mitigate the risks

In ensuring the above requirements, tools are needed to support the safety assessment. Cacciabue et al. (2015) show the need of *agility* and *user friendliness* for this tool in order to be used. Authors describe that the agility is essential to be able to support wide range of prospective and retrospective analyses that vary in scope, focus, and purpose, which may arise both from the regulatory expectations and from the organizations operational processes. Cacciabue et al. (2015) also describe that the tool must be required to address large number of different issues and perspective through adaptable analytical approaches. These benefits of agility are however only available if the tool is easy to be used. User friendliness therefore ensures that the methods for assessment are straightforward and effective in evaluating the risks. While multiple tools are available in the markets, in aviation two well-known are mostly established within the SMS: Bowtie and ARMS (Cacciabue et al., 2015). There are some larger differences between these, but in this research, focus in on bowtie, which will be further investigated in the next section.

Current SMS and bowtie practices mainly reflect a Safety-I perspective, seeking to prevent adverse events by identifying hazards and implementing controls. Hollnagel et al. (2015) explain, that in Safety-I, work is seen in binary way: either it is performed correctly or it fails. In this line of thinking, positive outcomes are credited to the system operating as designed and people acting in line with prescribed procedures, while negative outcomes are explained by faults, errors, or breakdowns in that intended mode of operations. In contrast, according to Hollnagel et al. (2015), the Safety-II concept starts from the idea that people constantly adjust how they work and that this variability is both inevitable and necessary, making it unnecessary to label elements simply as successes or failures, as the capacity to adapt and fine-tune performance is seen as a fundamental human strength that enables crucial work to be carried out at all. This research seeks to lens on both views: the bowtie-defined barrier specified in a Safety-I logic, while the empirical analysis of pilot reports and interviews draws Safety-II ideas of everyday performance.

2.2 Bowtie and barriers

Bowtie is a risk analysis method that has, as explained earlier, taken place amongst the most hazardous and complex industries such as gas, aviation, and mining. In aviation industry, bowtie is acknowledged as highly useful and recommended method according to multiple regulators and authorities, such as UK Civil Aviation Authority (n.d.), Polish Civil Aviation Authority (2020), and Australia’s Civil Aviation Safety Authority (CASA), who describes Bowtie as a analysis that allows stakeholders and risk owners to better understand risks, associated threats, consequences, and preventative and recovery controls (Australian Government Civil Aviation Safety Authority, 2023).

Lewis and Smith (2010) present multiple benefits of using bowtie method in operations, main benefits being *clear communication and improved understanding, greater ownership, and efficiency gains.* By clear communication, authors refer to clear identification of a hazard, meaning what can lead to it and how risks are controlled, making it easy for anyone from executives to the public to understand. Greater ownership contributes to bringing internal staff and other stakeholders together while encouraging open discussion and shared understanding according to the authors. Furthermore, they focus that by involving people who may not engage with traditional methods, bowties build commitment, accountability, and stronger ownership of process safety across all operational levels. Lastly, the authors highlight efficiency gains from using the bowtie method, noting that it requires less effort than many traditional approaches while clearly indicating where risk reduction efforts should be focused. Its visual clarity simplifies safety analysis, helps eliminate low-value barriers, guides maintenance and inspection toward critical controls, and supports the preservation of organizational knowledge, reducing the need for repeated rework.

In practice many companies use software for bowtie analysis, making it easier to adopt new hazards and barriers, and to improve the efficiency of mitigating risks according to Lewis and Smith (2010). Such software's are e.g. Bowtie Master, Bowtie Pro, and BowTieXP. Out of these options, according to Wolters Kluwer (n.d.), BowTieXP is the most used software enabling easy-to-read visual presentation of the bowtie, while clearly separating the preventative and corrective control methods. While multiple platforms for bowties exists, Lewis and Smith (2010) remind that many of the benefits of the process are carried out through active workforce involvement in brainstorming sessions. Software then adds value by quickly formalizing the diagrams and storing information for easy review, updating, and reuse.

De Ruijter and Guldenmund (2015) explore how bowtie has emerged through three historical developments: *Fault tree analysis, Event tree analysis, and Cause consequence* *diagram.* According to the authors, bowtie development started from *fault tree analysis* (FTA) in 1961 being based on Boolean-logic, where path towards the single top-event was constructed. It was often used in nuclear power plants, but reformatted to *event tree analysis* (ETA), that uses binary logic, leading to more compact analysis of the picture in around the 70s. ETA complements FTA by starting from an initiating event and analyzing possible outcome pathways, whereas FTA works in reverse by tracing the causes of an event. In the bowtie framework, ETA represents the right-hand side, while FTA corresponds to the left.

The top event, forming to the middle connecting FTA and ETA was developed also around the 70s as a *cause consequence diagram*, which is described as the first model of bowtie (de Ruijter & Guldenmund, 2015). In the article authors describe the formation of *barrier thinking* forming around the 70s, but by 2000s the idea of barrier management began to take its shape, as oil company Shell used it successfully in their operations (Badreddine et al., 2014). Barrier was eventually defined by Sklet (2006) as a "*physical or non-physical means planned to prevent, control, or mitigate undesired events or accidents*".

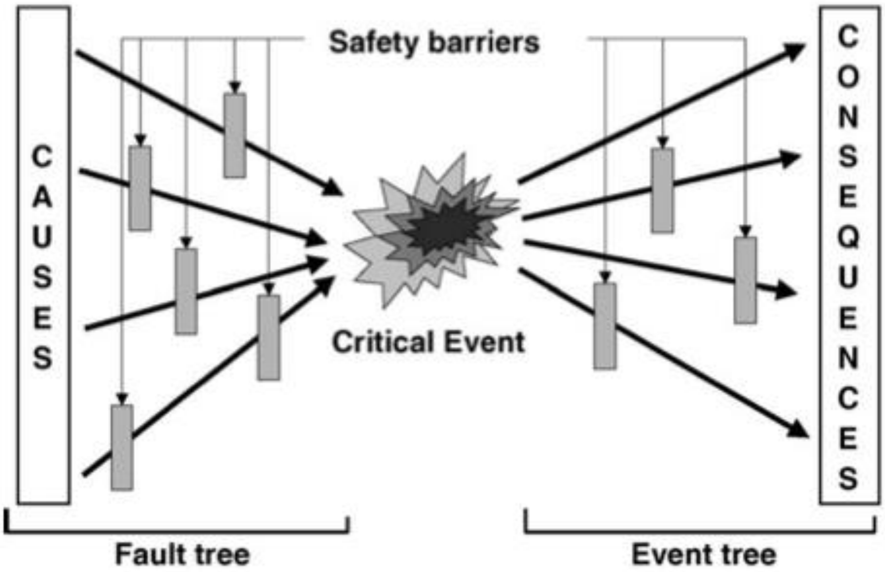


Figure 2. Complete bow-tie with identification of prevention or mitigation safety functions (de Dianous & Fiévez, 2006).

Bowtie model later developed into having three main components: *top event, causes and consequences, and barriers* according to de Ruijter and Guldenmund (2015). T*op event*, or *critical event* as in figure 2, is described by authors as the moment when control is lost, or more precisely, as the point where many negative events can occur just before consequences take place. Top events can be anything, but the audience should be kept in mind when determining it. De Ruijter and Guldenmund (2015) demonstrate that causes and consequences are exactly what the name suggests and can be integrated to the bowtie multiple ways having multiple reasons, while barriers may be implemented either to eliminate, prevent, recover or to mitigate the risks and effects. Eliminative and preventative barriers are placed on the left side of the top-event whereas recovery and mitigation are on the right (de Ruijter & Guldenmund, 2015).

Sklet (2006) defines the barriers more precisely regarding their function either as *passive* or *active*, and as *permanent* (integrated part of the whole life cycle) or *temporary* (used within specific time period). In the article, author explains that passive barriers can be divided either as physical barriers (e.g. firewall typically operating constantly not needing activation), or as human operational barriers (e.g. duty time limits or segregation of duties, usually implemented in accordance with high-risk activities). Active barriers may be activated once needed or working continuously. As figure 3 shows, active technical barriers can be extended to multiple safety related items, whereas with human operational barriers Sklet (2006) refers to barriers integrated within the work process, either by person itself or by third party, to reveal potential failures.

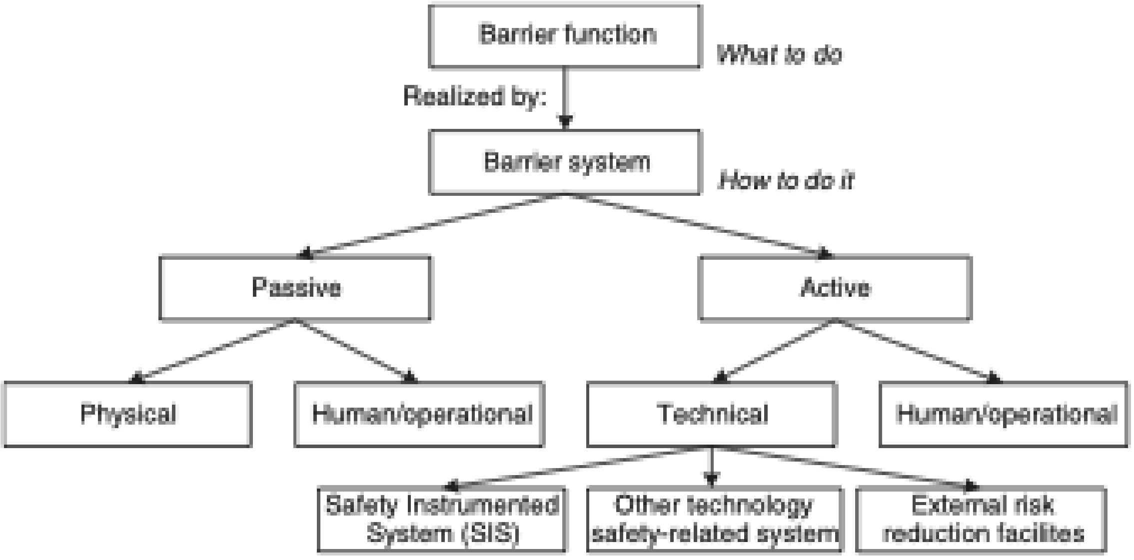


Figure 3. Classification of safety barriers (Sklet, 2006).

It is worth noticing, that safety barriers are not fully reliable and may exhibit both inherent limitations and temporary degradations. In bowtie methodology, conditions that reduce or influence barrier performance are referred as escalation factors, shown in Figure 4 (Aust & Pons, 2019). Escalation factor barriers are implemented to manage the escalation factors. The efficiency of the barriers is however not easily measured, although literature represents high demand for it. Issues related to performance of the safety barriers are largely considered within industries and academic literature, as these are directly related to the functions of the safety barriers (Qiao et al., 2022). Various research has taken views on whether to qualitatively or quantitatively analyze the effectiveness of barriers, but data gathering has proven to become an issue for proactive analyzing (Sklet, 2006).

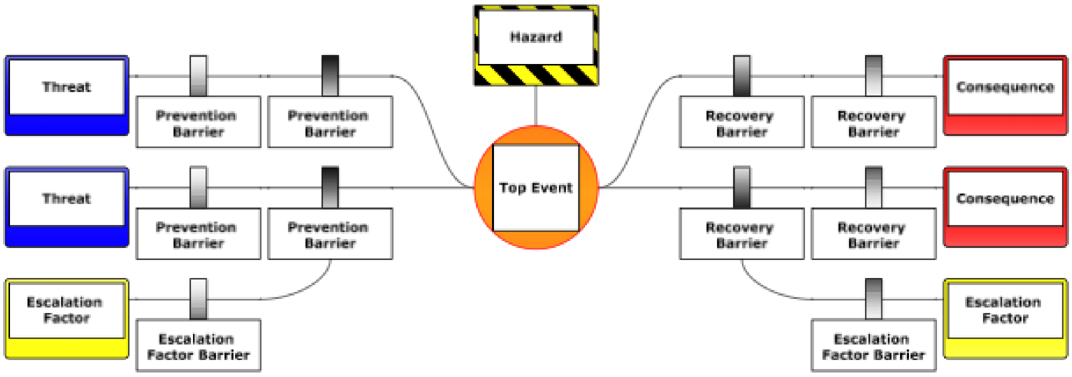


Figure 4. Schematic Bowtie diagram with prevention and recovery barriers (Aust & Pons, 2019).

In the next chapter, safety barrier effectiveness is discussed more thoroughly, with identification of how their performance has been analyzed within the academic literature. This creates foundation for the method section and the structure of the research.

2.3 Barrier performance

The definitions for performance criteria of safety barriers vary quite largely between the literature depending on the study and the industry it is related. Sklet (2006) studied the criteria establishment within multiple projects and literature to address five attributes characterizing the performance of safety barriers. These attributes are *functionality/effectiveness*, *reliability/availability*, *response time*, *robustness, and triggering event or condition.* However, depending on the scenario, some attributes might be more fit for specific application than others (Qiao et al., 2022). Followed by Sklet (2006), de Dianous & Fiévez (2006) identified three attributes being most relevant for the evaluation of the safety barrier. These attributes were: *functionality/effectiveness*, *reliability/availability*, and *response time*.

Barrier functionality/effectiveness is defined as the barriers capability to fulfill a defined function under specified conditions, e.g. technical, environmental, or operational, according to the study by Sklet (2006). This measurement relies mostly on functional requirement, stated out of the function itself, and can be expressed as a probability of success. According to the study, for safety barriers, these requirements can include e.g. regulations or standards. Furthermore, Fiorentini (2021) defines that the level of effectiveness of specific control measure can be expressed either qualitatively, semi-quantitatively, or quantitatively, using the method best suitable to demonstrate, whether the performance should be improved or new control measure adopted. According to de Dianous and Fiévez (2006), assessment of the effectiveness can be done during the risk analysis by considering data and experience from industry sources, along with results from on-site testing, applicable standards and technical guidelines, and calculation-based documentation related to the barriers.

Barrier reliability/availability is expressed as the capability to deliver the intended function with appropriate performance and timely response whenever activation is required, according to Sklet (2006). The article explains that the difference between the reliability/availability and functionality/effectiveness is, that while barrier may be reliable in terms of activation on demand, it still might exhibit reduced effectiveness if its performance is degraded. Thus functionality/effectiveness describes how well barrier performs in its intended function, while reliability/availability refers to likelihood that the barrier operates when required. De Dianous and Fiévez (2006) define barriers confidence level (reliability) as inversely proportional to probability of failure, reflecting barrier’s reliability to carry out its intended function with the required effectiveness and response time, under specified conditions and time period. Furthermore, they describe that before quantitative estimation of the confidence level, qualitative parameters should be studied to estimate level of confidence further.

Response time of a safety barrier corresponds to the interval between the occurrence of a deviation that triggers the designated barrier and the completion of its intended primary safety function (Sklet 2006). According to de Dianous and Fiévez (2006), when determining the response time for human barriers, it is influenced by several factors e.g., operator’s level of training, the clarity of diagnostic information, ease of access to the barrier, and the operator’s understanding of the required actions during the situation.

Performance of the barriers is also often related to the human performance, leaving organizations to struggle on how to ensure that required human actions can be reliably performed when needed, and that the associated controls remain resilient to reductions in human reliability. McLeod (2017) explain, that accident investigations often conclude that incidents could have been avoided if procedures had been followed. Article explains that this view assumes that procedures are complete, clear, current, accessible, and appropriate for the situation, and that personnel are sufficiently trained to recognize when and how to apply them under operational conditions. The assumption that safety depends solely on procedural compliance author deems as possible conflict with reality, where effective operations require informed judgment and adaption. Research highlights that the importance of clearly defining intended role of human operator and recognizing that safety is frequently maintained through their ability to adjust practices in real-world conditions. This distinction author refers to align with the concept of “work-as-imagined (WAI)” versus “work-as-done (WAD)”, where actual operations require continual adaption to situational demand altering the view on how we imagine the work to the actual completion of the work in reality.

In the magazine *HindSight* by Eurocontrol (European Organization for the Safety of Air Navigation) work-as-imagined and work-as-done is covered in one of the articles written by Hollnagel (2017), where reasons to the differences between how people think about work and way it’s actually done are discussed, while answering to the question on whether we can imagine how work is actually done. The article identifies that practical need for imagining the work done is needed when improving existing conditions and approaches – “*safety management must correspond to Work-As-Done and not rely on Work-As-Imagined”* (Hollnagel, 2017). According to the article this can be done either by finding assumed causes from happening again or by asking why things go right making sure it happens again, and by going out to operational environment. The solution to the gap between the WAI and WAD, Hollnagel (2017) suggests understanding the determining aspects on WAD and finding effective management to keeping variability of

WAD within tolerance. Furthermore, McLeod (2017) emphasizes that assessing the effectiveness of controls dependent on human performance requires a clear understanding of what the controls are intended to achieve and what is realistically expected from human action for the effectiveness criteria to be satisfied. This statement clearly correlates with findings in the article by Hollnagel (2017). Furthermore, this emphasis on understanding WAD rather than relying solely on WAI, aligns with the shift from Safety-I to Safety-II, where safety is also seen in terms of how operators adapt and maintain acceptable performance in everyday work.

McLeod (2017) also suggests that most organizational measures should be regarded as safeguards rather than primary barriers. These human and organizational safeguards would include actions and controls intended to influence behavior and reduce the likelihood of errors, ranging from warning systems to procedures and cross-checking practices, having primary function in supporting and protecting existing barriers from degradation, rather than delivering direct risk reduction. Paper mentions that particularly for human and organizational measures, whether a control functions as a barrier or a safeguard depends on the organization’s ability to implement and maintain it to the required standard over time. McLeod (2017) identifies eight following concerns from the CIEHF white papers report (McLeod & Randle, 2017), that can often be addressed in many bowtie analyses:

1st Top events are often placed too far right, occurring too close to the resulting consequences that barrier systems are intended to prevent

2nd Excessive number of barriers identified many of which do not satisfy criteria for effective barriers

3rd Barrier models often fail to adopt systems-level perspective on human and organizational factors underlying the threats they seek to manage.

4th Complexity of the tasks required for barriers to operate as intended is often insufficiently understood. Particularly their cognitive demands.

5th Lack of understanding on the gap between WAI and WAD

6th Human error often treated as a threat with barriers designed to prevent it from progressing to top event

7th Assumptions and expectations about performance in barrier designs are rarely made explicit or communicated to ones responsible for implementation, operating and maintaining these.

8th Barrier models are often developed and rolled out in ways that do not adequately support their practical use in operations.

Furthermore, Pitblado R et al. (2016) note, that barrier management is more static than dynamic, presenting development for dynamic barrier management as shown on Figure 5. The paper identifies how barriers with degraded performance may increase risk by either quantitively or qualitatively, and how the risk can be managed to return it to the target by operational decisions, introducing a risk management approach for both risk types. Qualitative risk approach includes tracking of barrier status and assigning a qualitative risk score (QRS) from 0 to 100 supported by categories of green (0-33), yellow (34-66), and red (67-100), where 0 represents nominal value with all barriers working, to support operational and strategic decision making. For quantitative risk approach, authors demonstrate three common issues with barrier management: *missing data for some barriers, limited awareness of available data, and excessive or unnecessary data analysis.* Report suggests that combining multiple datasets (e.g. training data from HR, incident data, etc.) may help to provide more context and lessen the over-analysis of a single dataset.

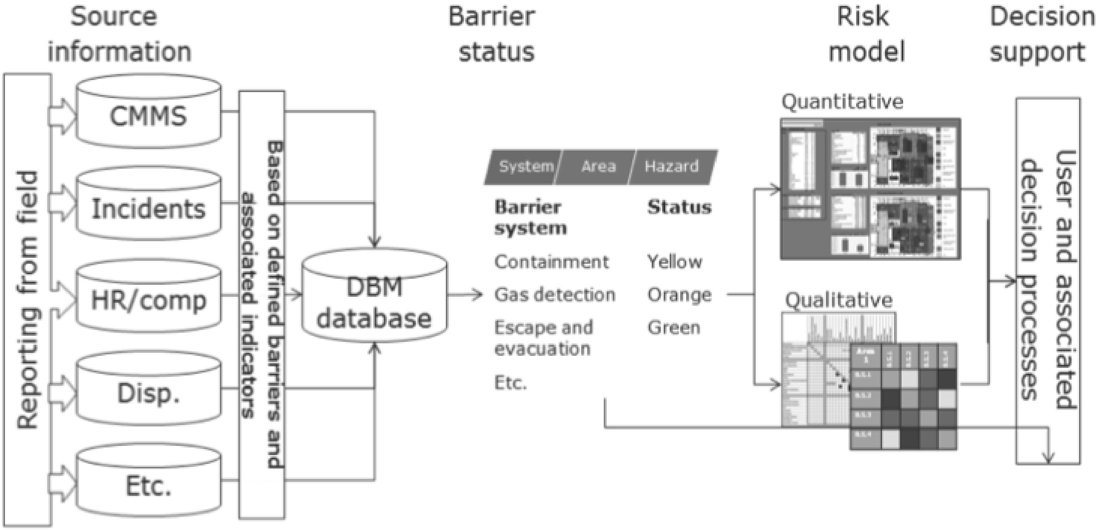


Figure 5. Concept for Dynamic Barrier Management (Pitblado R et al., 2016)

As the data sets can be large in qualitative assessment of barrier performance, authors imply to integrate technology to interrogate and identify trends among the data. Furthermore, Sneddon (2022) identify the need for key performance indicators (KPI) to capture the ongoing performance of the critical barriers. This correlates with the idea of integrating technology for data analysis by Pitblado R et al. (2016), by using intelligence tools such as Radiant360, PowerBI, Scoro, and Datapine. Technological advantage has also brough additional tools related to management of KPI's following the revolution of artificial intelligence (AI), but foundation for this in academic literature is still weak. However, some literature can be found, introducing the possibilities that could be achieved if used correctly. For example, Schrage et al. (2024) created global survey on organizations to seek how companies use algorithms in rethinking assumptions about results, profitability, and growth. It was concluded that organizations that integrate AI into their KPI's frameworks are three times more likely to achieve financial performance compared to those not.

Although the article is mostly based on financial enhancement using AI, the same principles could be potentially seen within safety related KPI's, as the research discovered that organizations in multiple industries are using AI to reassess the KPI's by redefining and clearly communicating more advanced metrics as part of their strategic measurement framework – further strengthening organizations capacity to achieve and optimize desired outcomes (Schrage et al., 2024). Furthermore, Van Gulijk and Mcculloch (2019) assessed that bowtie analysis enhances digital safety management by offering a structured approach for integrating digital barrier systems and remote monitoring. It also ensures that barriers using different data levels can be managed consistently within one safety framework. However, the key findings by Van Gulijk and Mcculloch (2019) include important note regarding the integration of AI into performance monitoring of bowties:

"It is not just a matter of introducing artificial intelligence for the prediction of barrier failures, it is also about integration of data-streams and the design of data-systems to support a plant or organization in it's entirety."

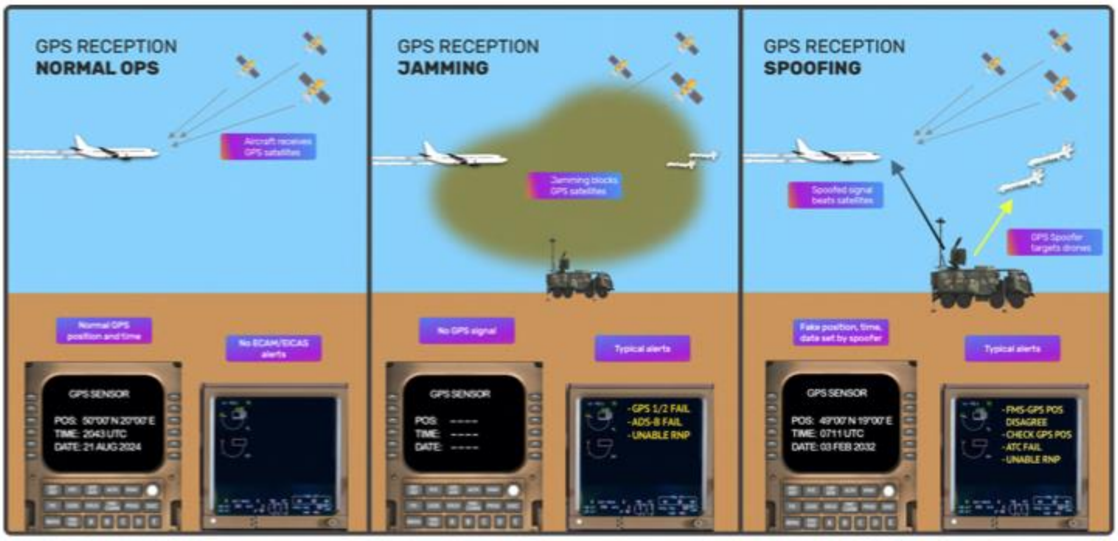
2.4 GNSS interference

In 1996, ICAO (International Civil Aviation Organization), formally recognized satellite-based navigation as a key element of the future civil aviation operations, highlighting improvements in safety, efficiency, and operational flexibility (International Civil Aviation Organization, 2018). Based on the report, since the endorsement by ICAO, several Global Navigation Satellite Systems (GNSS) have been deployed worldwide (e.g. European Galileo, Chinese BeiDou, and Russian GLONASS), with the Global Positioning System (GPS) being the earliest to achieve operational capability. GPS is a satellite-based radionavigation system that operates through constellation of 31 operational satellites circling earth at approximately 20 200 km transmitting radio signals to the users (National Coordination Office, 2025). Using these signals, users are able to define their position with an accuracy of a few meters, and with assistance systems down to few centimeters (National Land Survey of Finland, n.d.).

According to Kaplan and Hegarty (2017) the primary demand for GNSS navigation in aviation arose from oceanic operations, where ground-based navigation aids, such as

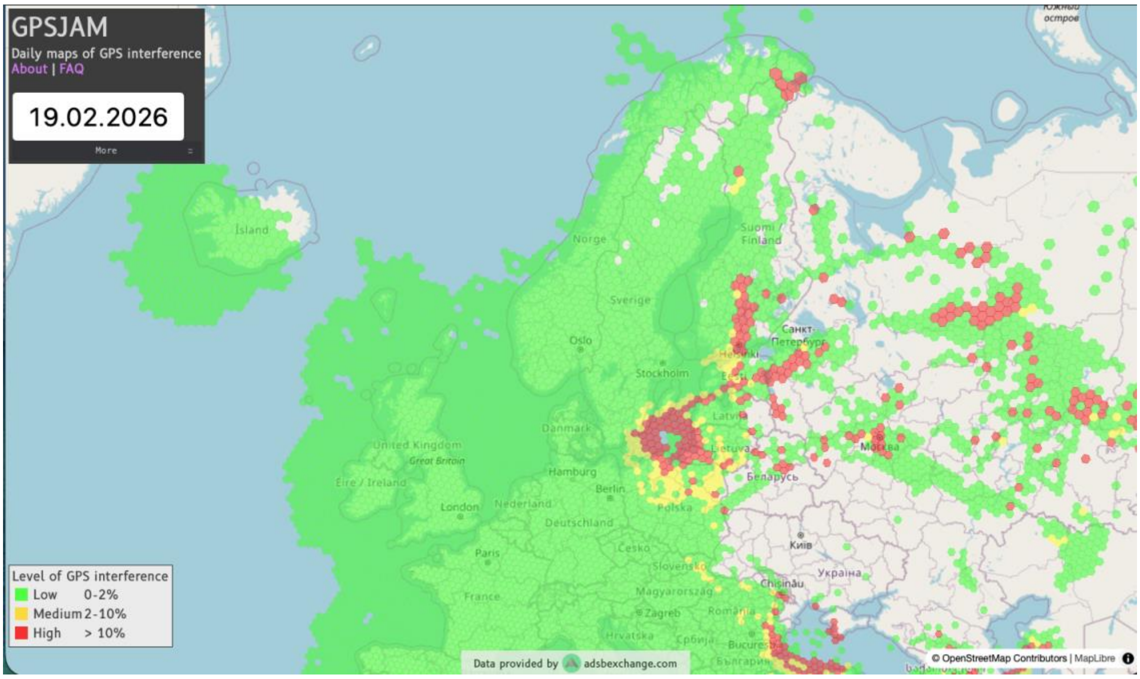
VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME) were unavailable. As airplanes were required to fly directly over these ground-based navigation aids, where airways normally converge, diverge, end and begin, it led to congestion of the airspace (Novak & Jurkovac, 2017). Navigation based on GNSS removes this need for direct overfly, enabling the usage of network of numerous virtual waypoints, that can be defined along routes, supported by satellite navigation, onboard systems, or ground-based aids, introducing flexibility in the operations as well as efficiency (Novak & Jurkovac, 2017).

According to the book by Kaplan and Hegarty (2017), GNSS can be applied to any phase of the flight, expected that the accuracy, integrity, and continuity of service are assured to be at an acceptable level demanded. However, GNSS receivers are vulnerable to radio frequency (RF) interference, that can be unintentional interference or jamming, or possibly spoofing, leading to degraded navigation performance or complete loss of tracking. According to SpaceFinland (n.d.), jamming corresponds to covering the signal with noise to make the receiver unable to separate the signal from it, failing to determine the position, whereas spoofing is explained as mimicking a false RF to make receiver think it is receiving genuine signal with incorrect data. In this research the focus is mostly on spoofing, but GNSS interferences are generally covered. Picture 1, screenshot taken from the OPSGROUP's technical guide (2024), illustrates these vulnerabilities by contrasting three situations: normal GPS reception, jamming and spoofing. In the first scenario, an interference source prevents the receiver locking onto the genuine satellites, leading to signal loss and degraded positional awareness. In the spoofing case, a ground-based transmitter imitates satellite signals and feed the receiver false data, so that the navigation display presents a seemingly valid but incorrect position, making this form of interference particularly problematic.



Picture 1. GPS Reception during normal ops, jamming, and spoofing. (OPSGROUP technical guide, 2024)

Globally GPS spoofing has increased rapidly impacting civil aviation in September 2023 starting with few flights affected, but by 2024 within one month observation period total of 41 000 flights had experienced spoofing (OPSGROUP, 2024). In Finland similar trend can be seen with exponential increase in GNSS interference and spoofing from 2022 to 2024 according to Traficom (Finnish Transport and Communications Agency) statistics (2024). GPS spoofing is a global phenomenon but usually concentrated in specific areas close to the conflict zones. Based on the report by OPSGROUP (2024), the highest spoofing levels globally were measured in eastern Mediterranean, Black Sea, western Russia, and between the border of India and Pakistan. According to the same report, in flight information regions (FIR's) of Vilnius, Tallinn, and Riga, 277 flights encountered spoofing within one month observation period from July 15 to August 15. Picture 2 below shows a screenshot on 19th of February 2026 from an online platform GPSJAM, which monitors GPS interference worldwide on a daily basis. Areas highlighted in red indicate the highest interference intensity, and the map clearly illustrates that these hotspots align with the regions identified in OPSGROUP's (2024) analysis.



Picture 2. Active GPS interference areas (https://gpsjam.org)

In Finland the responsibility to monitor GNSS frequencies nationwide is on Traficom which uses its own capabilities and GNSS Finland service operated by Finnish Geospatial Research Institute (Finnish Transport and Communications Agency, 2024). Furthermore, Traficom monitors interference affecting aviation and maritime, and inform operators through measures such as NOTAMs (Notifications to Air Missions) and navigational warnings to support preparedness for GNSS disruptions. OPSGROUP (2024) reported that for many air traffic control (ATC) centers especially spoofing has become a daily issue, with large rise in radar vectoring. Radar vectoring corresponds to a situation, where ATC gives pilots specific headings to fly, based on radar, to guide the aircraft safely for separation, routing or approach alignment. According to the same study, radar vectoring increases the workload and scanning availability for air traffic controller, especially if multiple aircrafts are being radar vectored at the same time. Overall, the research demonstrates that GPS spoofing has increased not only radar vectoring, but also incorrect tracks in departure, go-arounds, and uncoordinated climbs due to false GPWS (Ground Proximity Warning System) alerts occasionally leading to loss of separations. The workgroup of OPSGROUP (2024), studied the concerns related to GPS spoofing, using multiple reports (e.g. ATC and operator reports), and responses to surveys and analyses, eventually identifying eight main safety concerns. These concerns are following:

1st *Spoofing level increase.* A rapid rise of spoofing levels from 2022 with increasing intensity with more severe impacts. Systems affected and the complexity of the failures following the spoofing has shaped operational environment with new undetected risks.

2nd *Winter operations.* Winter operating conditions of darkness and poor weather introduce large increase in risk factors.

3rd *Risk of complacency.* The workgroup observed widespread complacency and low engagement within much of aviation industry, evidenced by slow response to GPS spoofing, delayed and incomplete crew guidance, and limited discussion of related safety risks, particularly GPWS effects.

4th *Complexity of GPS in systems.* GPS reliance across numerous critical aircraft functions has created a highly interdependent operational environment, making effective risk evaluation difficult and vital. Resulting variety of problem system degradation scenarios represents a significant operational and safety concern.

5th *Missing technical information.* It was identified that access to clear technical information regarding GPS integration, inconsistent operational guidance, and inadequate procedures, which contribute to knowledge gaps and misunderstanding. For example, deselecting GPS in FMS would safeguard EGPWS functionality.

6th *Possible degraded aircraft.* GPS spoofing can trigger widespread and cascading system degradations, resulting in unacceptable aircraft condition for dispatch. Crews may be compelled to continue flight in degraded state that would not be tolerated prior departure.

7th *Possibilities for worsening.* Although aircrafts have not yet been intentionally targeted, existing spoofing incidents reveal vulnerabilities with potentially severe consequences. At the same time, spoofing activity is becoming more adaptive in both location and technical complexity.

8th *Risk increase in emergencies.* System degradation increases workload and erodes situational awareness, raising baseline risk and significantly undermining crew effectiveness in emergency situations.

The literature review of GNSS allows us to identify its issues as one of the main risks affecting the safety of operations within Europe, providing more strength towards the study of barrier efficiency mitigating the risks. As the literature related to these issues is often described rather technically than operationally, it is necessary to integrate the operative view also in the context, to provide holistic approach to the research questions. The chapter number three, *Methods,* describes how this research does this using mixed method, through quantitative data collection from reports related to GPS spoofing, and through qualitative semi-structured interviews with pilots working in the operative field.

2.5 Summary of the literature review

This literature review has established the theoretical basis for examining how bowtie-defined safety barrier mitigates GNSS interference risks in airline operations. It showed how organizational risk management and ERM concepts frame safety controls within broader management systems and how in aviation, SMS provides the regulatory structure for identifying hazards, implementing risk controls, and verifying their effectiveness. Within this context, bowtie was presented as a widely adopted tool that visualizes hazards, threats, consequences, and barriers, while clarifying responsibilities and supporting communication across organizational levels.

The review then examined the nature of the safety barriers and their performance dimensions, highlighting factors affecting their real-world effectiveness, while identifying key performance attributes of *functionality /effectiveness, reliability / availability, and response time,* from prior studies. Furthermore, adding *human performance* as additional attribute, emphasizing strong human and organizational influences to determine how barriers perform in practice. Concepts of works-as-imagined versus work-as-done, together with the Safety-I and Safety-II, underline that procedural controls do not operate in isolation, but depend on operators' adaptive performance, and that many organizational measures may function more as safeguards than as primary barriers. Calls for dynamic barrier management, integrated datasets, and KPI-based monitoring, including emerging AI-supported approaches, further stress the need to move from static bowtie models to more responsive, data-driven barrier management in complex operations.

Finally, the review positioned GNSS interferences as rapidly escalating risk in civil aviation, particularly in the Baltic and Finnish regions, and described how GNSS technologies have become deeply embedded in airline operations. Technical literature shows, that jamming and spoofing can degrade or corrupt navigation information, while operational reports and OPSGROUP analyses indicate multiple concrete impacts, such as increased radar vectoring service from air traffic control (ATC). Together, the lines of evidence reveal a clear research gap of having limited empirical evidence on whether procedural barriers, intended to mitigate effects such as GNSS interference, achieve their intended effect in operations, and how their performance can be evaluated using operational and qualitative data. This gap motivates the present study's mixed-method design, using safety reports and pilot interviews to assess the effectiveness and performance modes of a specific procedural barrier, and to derive practical recommendations for barrier management in airline SMS.

3 Methods

Following the determination of the required quantitative and qualitative methods for understanding the efficiency of the safety barrier in bowtie analysis, as demonstrated by the literature review, the research uses mixed method approach in finding answers to the research questions. By using mixed method approach the depth of the data collection can be increased, as explained by Adeoye-Olatunde and Olenik (2021). The interviews for the qualitative primary data section of the research were conducted as semi-structured interview with Nordic Regional Airlines' pilots in ATR fleet and analyzed using deductive thematic analysis. The quantitative data regarding the reporting of the GPS spoofing and number of operations were obtained from Nordic Regional Airlines' reporting system. Both of the data collection methods are explained in this chapter.

3.1 Semi-structured interviews

According to Adeoye-Olatunde and Olenik (2021), semi-structured interviews are suited to research that seeks to capture participants individual perspectives rather than broad generalizations, finding strength in flexibility for emerging of ideas during the interview gaining deeper insight. As these ideas can't be obtained from quantitative data alone, combining it with semi-structured interview can enrich the quantitative findings as mixed method approach. Furthermore, Kallio et al. (2016) explain that primary advantage in using semi-structured interviews lies on how these permit interviews to be focused, while giving opportunity for the investigator to explore relevant ideas as they arise, leading to more deeper understanding of the subject.

The semi-structured interviews were conducted within the Nordic Regional Airline's ATR pilots. This interview consisted of 10 questions initially, related to four attributes discovered in the literature review. One question was later removed to reduce repetition, as the answers to the previous questions already addressed the same topic extensively. This reduced the final number of questions to nine, which can be found from appendices. The topics interviewed related to three main factors attributing to barrier efficiency by de Dianous and Fiévez (2006) of functionality/effectiveness, reliability/availability, and response time, along with attribute of human performance, introduced by McLeod (2017).

The invitation to participate in the study was distributed through the company's internal communication channel to multiple pilots, of whom eleven ultimately took part in the interviews. Interview appointments were scheduled individually and conducted via Microsoft Teams. Before the interview, interviewees were introduced to the subject by Powerpoint presentation of 4 slides, including general information regarding the Thesis, interviewer, bowtie, and the upcoming questions. The interviews were conducted in Finnish, after which the responses were translated into English for analysis. The questions are presented in Finnish in Appendix 1 and in English in Appendix 2. All sessions were recorded using the Microsoft Teams transcription function to enable accurate documentation and to enhance the reliability, validity, and overall rigor of the study. The duration of the interviews ranged approximately from 20 to 30 minutes.

The participant group included both first officers and captains from the ATR fleet. In total, eight first officers and three captains were interviewed, all with multiple years of background in commercial aviation. To preserve anonymity, no additional demographic information, such as age or level of experience, is disclosed. After each interview Microsoft Teams transcript was combined with the researcher's personal notes taken during the interviews, to produce finalized document for analysis. In total 11 documents were used for qualitative assessment, all following consistent structure.

3.2 Thematic analysis of the interviews

Thematic analysis is a commonly applied technique for examining qualitative data, providing a systematic but adaptable framework for discovering, interpreting, and describing recurring patterns or themes within the dataset (Ahmed et al., 2025). In deductive thematic analysis, the six-step process introduced by Braun and Clarke (2006) is commonly adopted to ensure rigor and creditability throughout the qualitative research. The steps include *familiarizing yourself with the data, generating initial codes, searching for themes, reviewing potential themes, defining and naming themes,* and finally *writing up.*

The research used these steps as the structure for the deductive thematic analysis, where the initial step included literature review analysis to identify common themes. Four attributes of functionality/effectiveness, reliability/availability, response time, and human performance were selected as the pre-defined top-level themes, forming the structure for coding and interpreting the data, but also for the interview questions.

Table 1. Findings of the deductive thematic analysis

Main theme	Subtheme	Descriptive label
Theme 1: Functionality / Effectiveness	1.1.	Proactive use strongly enhances barrier effectiveness
	1.2.	Technical limitations reduce functional performance
	1.3.	Spoofing detection difficulty undermines effectiveness of the barrier
Theme 2: Reliability / Availability	2.1.	Habituation reduces reliable activation
	2.2.	Activation based mostly on personal judgment
	2.3.	External navigation infrastructure limits the availability of the barrier
Theme 3: Response time	3.1.	Delayed spoofing detection due to workload or distraction
	3.2.	Spoofing onset often faster than pilot reaction time
Theme 4: Human performance	4.1.	Habituation and reduced vigilance over time
	4.2.	Procedure based on memory

The data was systematically coded using the four attributes, allowing subcodes to emerge. The pilot interviews were read in full multiple times to develop holistic understanding of how the barrier is used in real operations. Throughout this stage, early reflective notes were written to capture any patterns or observations. The transcripts were then coded using deductive approach. Rather than coding freely, the analysis used four attributes as priori coding categories. Each meaningful segment of text was assigned to one or more code groups. After the coding, all data was reviewed within their assigned attributes, allowing patterns to emerge in each category. These patterns created 10 sub-themes. that were checked against the complete data set to ensure these accurately reflected the pilots' experience and that no relevant material was excluded. Furthermore, each subtheme was then given descriptive label capturing its relevance to the research question. Finally, the results following the four predefined attributes as main themes are presented in Table 1. The results are further discussed in the results section.

3.3 Quantitative data analysis

The quantitative data consists of two datasets provided by Nordic Regional Airlines. The first dataset includes operational reports written by pilots, published through company's reporting system. The dataset was filtered using the search terms "GPS," "interference," "spoofing," and "jamming," combined using the Boolean operator OR, revealing 807 reports for all aircraft types following the time period of 9.2.2022 to 28.1.2026. The information provided in the dataset included the ID number of the report, the date of occurrence, description of the occurrence, event type, aircraft type, and the location of the occurrence. The second dataset included the number of operations (flights) per month from December 2021 to December 2025.

The first dataset was initially reformatted using Microsoft Copilot Artificial Intelligence to identify keywords out of the descriptions of the reports. The keywords identified from the descriptions are listed in the Table 2. Each of the reports including keyword was marked either as "TRUE" if found or "FALSE" if not found. The findings were then listed in new listing including all of the events and furthermore abstracted to show monthly statistics of the reports. The variables that were presented in the monthly table are shown in Table 3. Using the monthly statistics, multiple quantitative indicators were constructed to assess the performance of the bowtie barrier *"GPS disabled in critical airspaces"*. All indicators were calculated on a monthly basis for the study period.

Table 2. Keywords used for description analysis

Description	Keyword
Spoofing	"spoof"
Vectors	"vector"
Jamming	"jam" OR "interfer"
EGPWS	"egpws" OR "terrain"

First, a frequency indicator “Exposure index (spoofing reports per 1000 flights)” was defined as the number of reports classified as the spoofing events reported in a given month (**Spoofing**) divided by the total number of flight operations in that month (**TOTAL)**, multiplied by 1000. This indicator describes how often spoofing events were reported in the reports relative to traffic volume and is used for characterizing changes is exposure over time.

Second, a combined severity indicator “Severity index (spoofing with vectors per 1000 flights)” was calculated as the number of spoofing related reports that involved ATC vectoring (**Vectors_+_spoofing)** divided by the monthly number of flights **(TOTAL)** and multiplied by 1000. This indicator represents the rate of spoofing events requiring vectoring per 1000 flights, combining information on both exposure and escalation into a single measure of operational safety impact. Furthermore, a “GNSS severity ratio” was constructed to indicate when the GNSS disturbances become operationally significant and how these changes over time. The ratio was calculated dividing spoofing related reports involving ATC vectoring (**Vectors_+_spoofing)** by all GNSS disturbance reports in each month (**TotalEvents).** In addition to the severity index and ratio, a separate vectoring rate was calculated as all events involving ATC vectoring per 1000 flights per month, irrespective of whether the disturbance was coded as spoofing or as interference, dividing all vectoring events **(Vectors)** by monthly number of flights **(TOTAL)**, and multiplied by 1000.

Third indicator, “Escalation KPI (spoofing with vectoring per all spoofing in month)” was defined as the number of spoofing related reports that explicitly involved ATC vectoring (**Vectors_+_spoofing)** divided by the total number of spoofing related reports in the same month (**Spoofing)**. This ratio reflects the proportion of spoofing events that escalated to the point where vectoring support was used and is therefore treated as the primary quantitative indicator of how effectively the barrier helps crews manage spoofing without escalation. To express the escalation behavior from barrier-centered perspective, a Barrier Effectiveness Index (BEI), was further constructed from the escalation KPI. BEI is defined as 1- (escalation KPI), and supports the findings as a useful measure, expressed in percentage, to demonstrate barriers probability to failure.

Based on the results of the indicators, Pearson correlation was calculated using Excel’s own correlation function between the escalation KPI and exposure index. This correlation was first computed for the full study period to assess whether higher spoofing exposure was generally associated with a higher proportion of events requiring vectoring from the ATC. To explore potential learning over time, the series was further divided into an early (by 03-25) and later (after 03-25) phases, and the correlation was calculated separately for each, allowing examination of whether the relationship between exposure and escalation changed as crews accumulated experience with spoofing and the barrier procedure. All of the quantitative indicators are discussed further in the results section, including the results of the interpretations of plots individually and combined.

Table 3. Description of the variables in monthly statistics

Variable	Description of the variable
YearMonth	A year-month identifier (YYYY-MM) assigned to each event or aggregated row. Used for monthly grouping of interference reports and normalization.
Spoofing	Binary indicator (TRUE/FALSE) showing whether the event description contained spoofing related terminology.
Jamming	Binary indicator (TRUE/FALSE) showing whether the event description mentioned GPS jamming or signal interference related terminology.
EGPWS	Binary indicator (TRUE/FALSE) showing whether the event contained EGPWS (Enhanced Ground Proximity Warning System) warning
Vectors	Binary indicator showing whether the crew required heading or radar vectors from ATC due to GPS interference or loss of navigational capability.
TotalEvents	Number of all GPS interference related events recorded for a given month (sum of all rows to that YearMonth)
ATR	Total number of ATR fleet flights for that month
EMB	Total number of Embraer fleet flight for that month
TOTAL	Combined number of ATR + Embraer flights that month
TotalEvents_per_1000	Normalized rate showing how many total interferences occurred per 1000 flights in a given month
Spoofing_per_1000	Normalized rate showing spoofing related events per 1000 flights
Jamming_per_1000	Normalized rate showing jamming related events per 1000 flights
EGPWS_per_1000	Normalized rate showing EGPWS related events per 1000 flights
Vectors_per_1000	Normalized rate showing vectors required per 1000 flights
Vectors_+_spoofing	Number of spoofing related reports explicitly including vectoring
Vectors_+_Spoofing_per_1000_flights	Rate of spoofing events requiring ATC vectoring per 1000 flights
KPI	Rate of spoofing events requiring ATC vectoring per 1000 flights, relative to the total spoofing events reported for the same period

4 Results

The results section presents the findings from both the qualitative interviews and the quantitative data analysis, followed by an integrated interpretation of the combined results. The section begins with the outcomes of the qualitative interviews, structured according to the items listed in Table 1, after which the quantitative findings derived from the reporting data are discussed in detail.

4.1 Interview findings

The interview findings are shown below according to the order presented in the methods section table 1. These results present the findings from the interviews with ATR pilots. The purpose of this section is to examine the operational performance of the barrier at general, organizational level, rather than to compare fleets. For this reason, only ATR pilots were included in the interview sample. Although Embraer pilots are not included in the interviews, the failure modes, behavioral patterns, and challenges related to the barrier identified, are considered relevant across fleets.

4.1.1 Theme 1: Functionality / Effectiveness

The first predefined attribute determining the barrier's performance in the qualitative analysis was *functionality/effectiveness*, referring to how well bowtie barrier (GPS disabled in critical airspaces) performs its intended purpose of preventing the navigation degradation during the time of spoofing. Across the eleven ATR pilot interviews, three consistent subthemes emerged, which are listed in Table 4 below. Each of the subthemes will be discussed in detail individually. Together these findings illustrate that the barrier can be highly effective, but its functional value is heavily dependent on timing, system capability, and situational awareness.

Table 4. Theme 1 subthemes

Subtheme	Descriptive label
1.1.	Proactive use strongly enhances barrier effectiveness
1.2.	Technical limitations reduce functional performance
1.3.	Spoofing detection difficulty undermines effectiveness of the barrier

The first subtheme "*Proactive use strongly enhances barrier effectiveness"* is a prominent and consistent finding across the interviews that the barrier is highly effective when it is applied before the aircraft enters a known spoofing area. Pilots who routinely used the given barrier procedure in advance described the barrier as preventing nearly all adverse consequences associated with spoofing. Multiple interviews consistently portrayed the proactive usage as the most effective method to increase the effectiveness of the barrier. For example, interviewee 2 estimated, that "*if used proactively, about 90 percent of spoofing cases can be prevented, but it requires that you need to be proactive with it".* Furthermore, Interviewee 3 described that "*The procedure is almost 99 percent effective when used proactively"*, while interviewee 10 noted that "*I would say 100 percent effective – I haven't had any problems",* and interviewee 11 *"It is effective when GPS is disabled in time.".*

Several pilots also emphasized the importance of anticipating spoofing hotspots, rather than responding to cues reactively. The listed hotspots from the interviews are presented in figure 6. The procedure used for proactive anticipation included preparing the aircraft for entering the critical areas in advance, by deselecting at least one GPS receiver, transitioning to DME/DME navigation to maintain navigation accuracy.

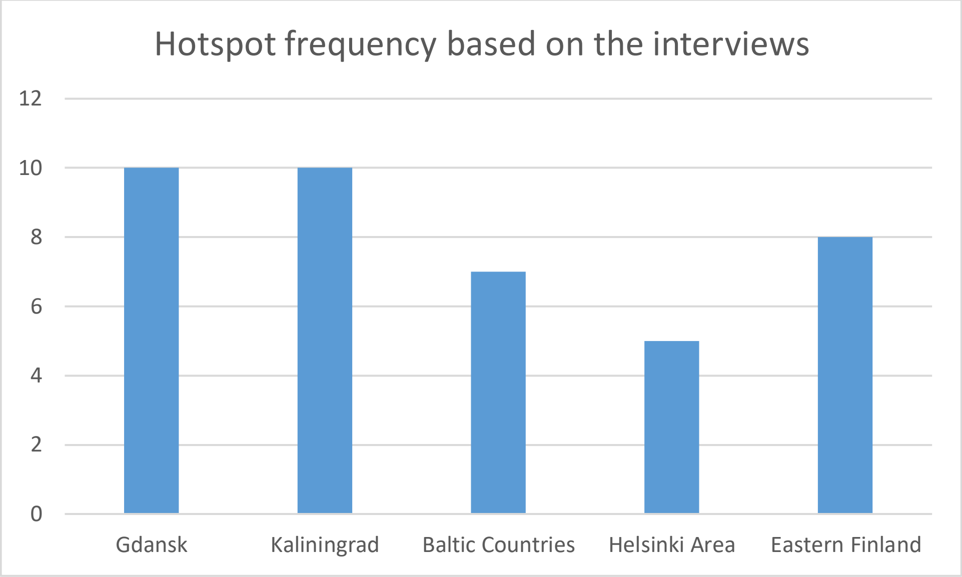


Figure 6. Hotspot frequency based on the interviews

The interviews revealed clear consensus, that the barrier works extremely well when used proactively, forming the strongest performance factor across all four attributes. When the threat is anticipated and reacted in time, the negative effects rarely materialize, although the variation across the pilots is large when and how the procedure is applied.

The second subtheme "*Technical limitations reduce functional performance*" highlights that the barrier's effectiveness is constrained by the technical behavior of the navigation systems, when the procedure is used. Pilots reported several functional limitations that reduce the barrier's protective capacity, showing that the barrier's functional protection is not purely procedural, but limited by the quality and availability of the aircrafts alternative navigation systems. As the subtheme concerns mostly highly technical system-specific behavior that falls partially out of scope of this qualitative analysis, these aspects are acknowledged but not explored further. However, concluding the findings of this subtheme, it can be noted that when the following systems perform well, the barrier functions well. However, once not, the barrier's performance degrades greatly.

The third subtheme concerns the limitations in detecting spoofing early enough for the barrier to work as intended. Pilots repeatedly described spoofing as subtle, gradual, or difficult to notice, which often resulted in delayed activation of the procedure. Moreover, some interviews expressed concern that during high workload phases, such as approach, departure, or landing, early detection might be even more difficult. Several interviews reported experience of small or incremental drift, which did not immediately trigger suspicion:

"Small spoofing is really difficult to detect – it might take a larger effect to notice it." (Interview 1)

"Spoofing comes gradually…recognition time can be from 15 seconds to 1.5 minutes." (Interview 3)

"Quite used to spoofing making large changes, but it can be of course more subtle spoofing, what could be harder to notice." (Interview 8)

Across all interviews, the barrier's functional performance is determined by three interrelated factors: *timing, system capability,* and *detectability*. When the procedure is used proactively in known hotspot regions, the procedure is regarded as highly effective in preventing spoofing-related issues. However, technical limitations can inhibit the barrier's protective effect. Furthermore, as spoofing can be subtle and gradual, pilots may recognize it only after it has already affected aircrafts systems, reducing barrier's functional value. Overall, Theme 1 shows, that barrier's functional effectiveness is high when used early under supportive technical conditions, but significantly reduced when put into action late, or when alternative navigation systems do not provide backup immediately.

4.1.2 Theme 2: Reliability / Availability

The second predefined attribute concerns *reliability/availability*, referring to how consistently the barrier is applied and how reliably it operates once required. Across the eleven ATR pilot interviews, three strong subthemes emerged presented in Table 5 below. The findings indicate that although the barrier can perform effectively when used proactively, its reliability is variable, significantly shaped by human and environmental factors.

Table 5. Theme 2 subthemes

Subtheme	Descriptive label
2.1.	Habituation reduces reliable activation
2.2.	Activation based mostly on personal judgment
2.3.	External navigation infrastructure limits the availability of the barrier

A key pattern across the interviews was that habituation has increased highly towards GNSS issues due to its chronic and routine presence in daily operations, leading pilots finding these as a “background noise” and not responding immediately, as required for proactive barrier action. Almost every interview included the habituation towards the interference.

“GPS interference is daily, so you don’t think about it that much anymore as you did previously” (Interview 7)

“*The light is on all the time; you don’t pay much attention” (interview 10)*

“Level of interest has decreased as we see it every day” (Interview 3)

This normalization of deviance creates a direct degradation pathway, since if crews no longer perceive interference cues as abnormal or hazardous, the motivation towards the usage of the barrier’s procedure is lost, even in known hotspot airspaces. Throughout the interviews pilots acknowledged this openly, describing an internal shift from vigilance to routine acceptance, meaning that the barrier – while functional on paper – becomes unreliable in practice, as its activation depends heavily on pilot's perception of risk. When risk perception is suppressed, activation becomes delayed or skipped.

The second subtheme relates to the variability in barrier usage. Pilots repeatedly reported that the activation of the procedure is not governed by consistent triggers, but by intuition, habit, or context-specific decisions resulting in inconsistent application across crews. The variability of the barrier usage reflects pilots' differing experiences, confidence levels, levels of exposure to spoofing levels, and individual interpretations of the given instructions, such as bulletins. Examples of this retrieved from the interviews include:

"Depends on the day and how much I feel like it" (Interview 2)

"My action is really reactive, and rarely proactive." (Interview 8)

"If GPS is working and there's no interference, I won't necessarily disable it" (Interview 4)

"It's not really that clear, no. There haven't been any clear guidelines given for it, so the decision-making is pretty much left on our own shared knowledge and partly to the intuition as well." (interview 9)

"I use it with low barrier, as it can be expected anywhere at any time." (Interview 10)

Consequently, the reliability of the barrier is crew-dependent, context-dependent, and highly variable. Even experienced pilots reported that they sometimes use barrier proactively, sometimes reactively, and sometimes not at all – despite the exposure to the same risk environment, highlighting the gap between WAI and WAD.

A third reliability related finding concerns limitations in the external navigation infrastructure, which affects how dependable the barrier is once activated. Pilots reported, that in regions with limited DME/DME availability or insufficient ATC radar vectoring support, the barrier can become operationally unreliable. This however is deemed quite rare within the pilots, as the infrastructure of DME/DME and ATC radar vectoring is relatively good within the operational area.

The limitations constrain the availability of alternative navigation sources once GPS is disabled, meaning that the barrier cannot reliably function. Moreover, several pilots felt that the spoofing has regional variability, being more unpredictable and random, for instance in Finland, making proactive activation based on location less reliable. Again, as the infrastructure concerns mostly highly technical system-specific behavior that falls partially out of scope of this qualitative analysis, these aspects are acknowledged but not explored further. However, in conclusion it can be said that the reliability of the barrier is not only dependent on pilot behavior but also on the technical environment available in different regions.

The theme 2 demonstrates that the reliability and availability of the barrier are highly variable across pilots, flights, and airspace regions. While the barrier is structurally simple, its dependable activation is still undermined by habituation, intuition-based activation patterns, and navigational infrastructure constraints. The cumulative effect is, that although the procedure can be effective when used proactively, its operative reliability is uneven. This helps explaining why, even after the procedural improvements, some months show increased dependance on ATC vectors, as revealed in the quantitative analysis later on. The reliability attribute therefore represents one of the key areas where the barrier’s performance can degrade in operational settings. However, in multiple interviews, pilots described that they have been using the procedure in recent days, showing that the barrier is used widely.

4.1.3 Theme 3: Response time

The third predefined attribute concerns response time, referring to how quickly the barrier can be activated and interference detected. Across the interviews, two clear subthemes emerged presented in Table 6. Taken together, these findings illustrate that the response time component of the barrier is one of its most vulnerable attributes, as both detection and reaction are heavily constrained by human cognitive limits and the nature of the spoofing event.

Table 6. Theme 3 subthemes

Subtheme	Descriptive label
3.1.	Delayed spoofing detection due to workload or distraction
3.2.	Spoofing onset often faster than pilot reaction time

A consistent finding across the interviews was, that especially spoofing, is not always detected immediately. Pilots described situation where attention was divided or focused on secondary tasks, causing subtle spoofing cues to go unnoticed until the effects became more obvious. Spoofing does not always announce itself with distinct warnings but instead position drift or small anomalies can accumulate gradually.

"During cruise flight you might be doing something else, if you're not scanning right then, detection takes longes" (Interview 7)

"Small spoofing events are harder to detect; it takes a larger effect to notice it." (Interview 1)

The comments show that the detectability of the spoofing is highly variable and influenced by what pilots are doing at the moment the interference begins. Secondary tasks such as reading charts, taking the weather report, or simply handling routine cockpit duties draw attention away from the possible cues. Furthermore, pilots described that sector changes and airspace transitions further contribute to divided attention. As the barrier is preventative in nature, any delay in detection directly reduces its functional value. The later the spoofing is noticed, the narrower the remaining window for successful activation of the procedure is. Detection delay therefore forms a primary barrier degradation aspect within the attribute of response time.

Even if the spoofing is detected promptly, pilots reported that the onset can still outpace ability to respond, which outlines the second subtheme of the theme. Spoofing may induce sudden lateral deviations, creating possibly abrupt position jumps. These events require pilots to first diagnose what is happening before taking action, adding slightly time-consuming interpretation stage to the barrier's response time.

"It's fifty-fifty whether you can manage to switch the GPS to deselect or not." (Interview 2)

Across the interviews, the statements reflected that the reaction time cannot be instantaneous, as even fast and well-trained reaction involves noticing the deviation, confirming the spoofing, selecting the GPS off, verifying that there are alternate navigation systems available, and stabilizing the path if disturbed. On top of this, if the spoofing has evolved further, ATC needs to be informed, and vectors requested. This multistep chain represents that even minimal delays can give spoofing enough time to affect position accuracy or automation behavior. Furthermore, pilots emphasized that once spoofing has already corrupted the system's position estimate, disabling the GPS does not immediately restore accuracy – further reducing the benefit of rapid action.

The theme demonstrated that even highly capable pilots face structural limits in how quickly they can respond to a rapidly evolving spoofing event. The barrier's effectiveness is therefore limited not only by detection, but also by the inherent delay built into human-supervised action cycles. In barrier's view, response time can be seen as a critical bottleneck performance wise. Detection delays reduce opportunities for timely activation, and secondly even if recognized quickly, its inset can still progress faster than pilots can execute the necessary procedures. The findings offer a clear explanation for why some spoofing events escalate into situations requiring ATC vectors, as reflected in quantitative indicators, and underline the limitations of humans responding to fast developing anomalies. The theme also highlights how valuable the proactivity and preventative action taking is when it comes to these situations where recognition is limited.

4.1.4 Theme 4: Human performance

The fourth predefined attribute concerns human performance, referring to the behavioral, cognitive, cultural, and procedural factors influencing on how the barrier is applied during spoofing events. Across the interviews two clear subthemes were recognized. These are listed in the Table 7. The findings of the theme show, that the barrier's performance is heavily influenced by human cognitive limitations, with direct implications for response timing, consistency, and overall reliability. However, the subthemes also show that the human performance is both the largest source of degradation for the barrier, and in some cases the strongest source of compensatory safety behavior. The effectiveness of the barrier is therefore closely tied to human operational reality rather than purely procedural design.

Table 7. Theme 4 subthemes

Subtheme	Descriptive label
4.1.	Habituation and reduced vigilance over time
4.2.	Procedure based on memory

One of the strongest patterns in the dataset was the widespread habituation to the GPS interference. Across pilot's accounts, spoofing and other GNSS anomalies were described as so frequent that they no longer triggered heightened alertness. Instead, interference has become an expected part of normal operations, which reduces vigilance and undermines proactive barrier activation. Several descriptions of habituations were documented through interviews:

“GPS interference is daily, so you don’t think about it that much anymore as you did previously” (Interview 7)

“*Well, regarding the habituation, interference is present all the time and that’s the issue. You just have learned to live with it as time has passed.” (interview 10)*

“Level of interest has decreased as we see it every day” (Interview 3)

“GPS interference no longer fazes; it has become more of an “normal operation”.” (interview 8)

“When you fly regularly in these areas, you become desensitized, you see it every day” (Interview 3)

This desensitization is closely tied to operational exposure. Pilots who frequently operate in these hotspot areas explained that the interference becomes so common that its perceived urgency decreases. The reduced vigilance affects both detection and activation of the barrier. When interference cues no longer trigger immediate suspicion, pilots may not activate the barrier proactively, especially when entering the known hotspot areas. Some pilots openly acknowledged that the interference *“No longer causes reaction it did initially” (Interview 11)*, with typical response being *“Just wait, it will probably come back” (Interview 11).*

This normalization of deviance means that the barrier is often activated too late or not at all, thereby weakening its intended function. Habituation therefore represents a significant human-performance pathway through which the barrier’s operational effectiveness can degrade.

A second major subtheme of human performance concerns the extend which the barrier depends on memory-based actions. Because the procedure must be manually selected at the appropriate moment, its application is highly vulnerable to memory lapses, distractions, or competing task demands – especially in a high workload environment, such as take-off, landing, or approach. Interviews revealed, that as the procedure is based on memory, it has forgotten sometimes:

"The only unreliable thing that comes to mind is that if you forget to take the GPS off, or both forgets to take them off, and plane is spoofed – then it's a bit awkward situation" (Interview 10)

"I haven't had too many flights near the hotspots, but as sometimes you can be bit scatterbrained, I feel like not using it that much since I would probably forget the GPS's off" (Interview 8)

"Well sometimes we have talked in the previous segment that lets remember to reset the GPS on ground as we took them off in the air, but then it's forgotten" (Interview 9)

The statements illustrate, that the barrier require pilots to remember when and where to apply it, to track whether it's active, and to ensure systems are configured correctly through different flight phases. The reliance on memory creates clear structural vulnerability to the barrier, even when the pilots understand the procedure and its benefits, interruptions or workload peaks can easily cause the procedural step to be overlook.

Memory-based degradation interacts with other themes, for example, as habituation reduces the visibility of interference cues, it leads to pilots forgetting to activate the barrier proactively. Furthermore, as high workload delays actions, it leads to pilots forgetting to engage the barrier especially within the hotspot regions. Together these findings show that the barrier relies on quite proactive timing and recall of the crew.

When memory slips occur, the barrier can fail silently, increasing the exposure to the spoofing effects. The theme demonstrated that human performance factors significantly affect how well barrier functions in operational practice. The findings underscore that reliability is shaped also greatly by human attentional dynamics and cognitive limitations.

Although the theme mostly highlights human factor vulnerabilities, the interviews revealed that pilots provide adaptive, anticipatory, and corrective actions that highly extend the protective capacity of the system when used correctly. Many interviewees described extensive use of cross-checking practices and other navigational systems, helping to detect the anomalies early. Furthermore, pilots demonstrated strong geographical awareness and anticipatory airmanship, especially within the hotspot regions. Interviewees also highlighted the importance of timely escalation to ATC vectoring when positional confidence was lost, demonstrating practical judgment and situational responsiveness. These behaviors effectively compensated when the barrier was activated late or when technical limitations reduced its performance. Taken together, the findings show that while being a source of degradation through habituation and memory lapses – it also serves as a key contributor to system reliance, providing adaptive experience-based actions to strengthen the overall safety during spoofing events.

4.2 Flight report analysis findings

The results of this section are obtained by using the methods described in the chapter *Methods*, and using the variables introduced in Table 3. The results of exposure, severity and KPI indicators are first explained in detail individually, which after the results from the thorough interpretation between the indicators are introduced, along with fleet comparison and other findings.

4.2.1 Exposure

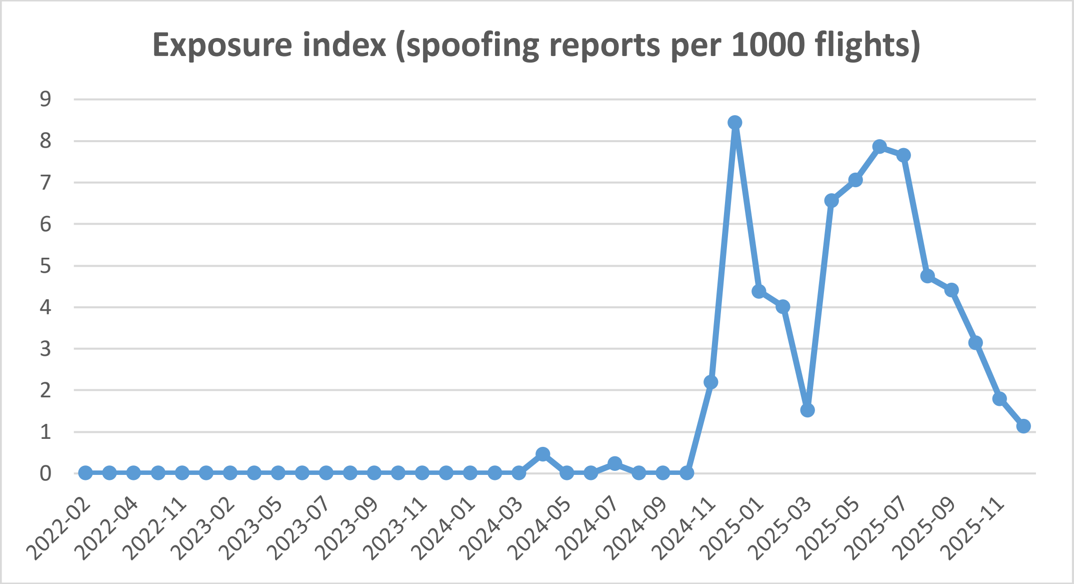


Figure 7. Exposure index (spoofing reports per 1000 flights)

The *exposure index* plot in figure 7 above shows, that GPS spoofing reports were essentially absent or extremely are until 2024, after which there is a marked increase. In the first half of 2025, a sharp climb of rate can be seen from near zero to distinct peak of roughly 8 spoofing reports per 1000 flights, indicating concentrated period of elevated spoofing exposure or, at minimum, heightened reporting of such events. After the peak, rate drops back down, followed by second lower “wave” during 2025, before declining again towards the end of observation period.

Overall, pattern suggests that spoofing is not a stable background risk, but more wave type, likely driven by specific geographical or operational factors (e.g. flight operation increase to more critical regions). For evaluating the barrier, it’s important to recognize that exposure to spoofing changed markedly over time. Therefore, simply comparing the numbers of events before and after implementation would be misleading unless the figures are first normalized by the number of flights.

4.2.2 Severity

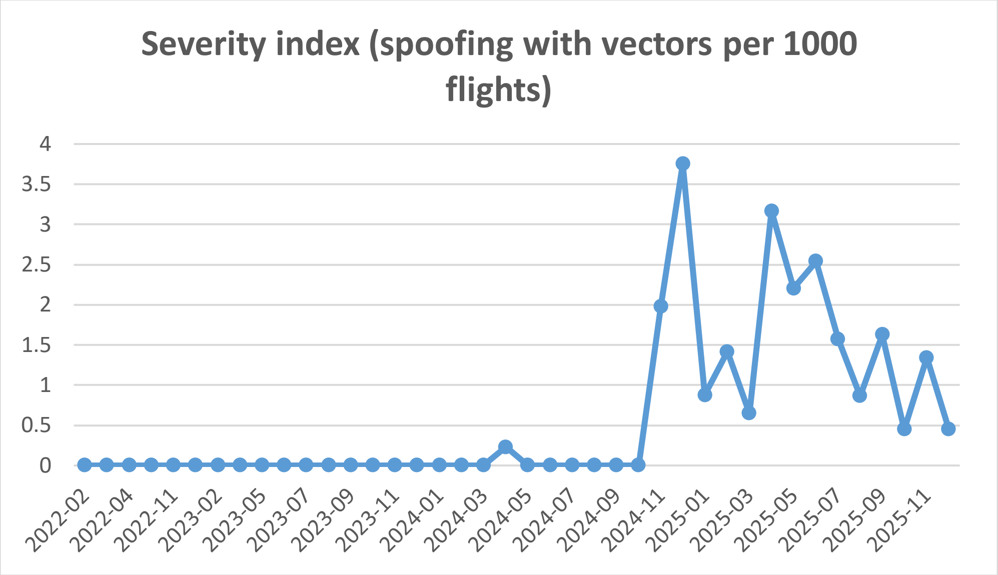


Figure 8. Severity index (spoofing with vectors per 1000 flights)

The second, combined *severity index* in figure 8, represents the rate of spoofing events that required ATC vectoring, normalized by traffic volume. During the initial period with virtually no spoofing, the rate is mainly zero. When the first major wave of spoofing occurred in 2024, the rate can be seen increased as spike, indicating that not only are spoofing events more frequent, but a substantial number of them are requiring vectoring. In the subsequent period, as the overall spoofing exposure decreases and rises again, the rate follows a similar wave pattern but does not reach similar peak levels as seen during the first wave exposure months. Towards the end of the series, both figure 7, and figure 8, indicate decline, suggesting reduction is overall operational burden of spoofing events that require ATC intervention.

Furthermore, for more comprehensive determination of the impact of GNSS interference, a *GNSS severity ratio* (figure 9) was constructed to show when the disturbances start to become operationally significant and how it changes over time. As the figure shows, for a long time the GNSS disturbances remained at zero indicating that the anomalies did not translate into spoofing and vectoring events. Once the spoofing began to appear, the severity ratio increased sharply, with peaks up to 0.45, meaning that in some months almost half of all GNSS reports included spoofing requiring vectoring. During the main exposure period, the severity ratio fluctuated in the range of roughly 0.1 to 0.36, while in the final months of the documented series, showing renewed high ratios of around 0.4 to 0.55. The patterns indicate, that when spoofing is active, the GNSS disturbance reports become increasingly dominated by operationally significant event, rather than minor anomalies, but like other KPI's introduced, it is limited by small numbers and reporting dependence, where small changes to numbers can cause large effects in plots.

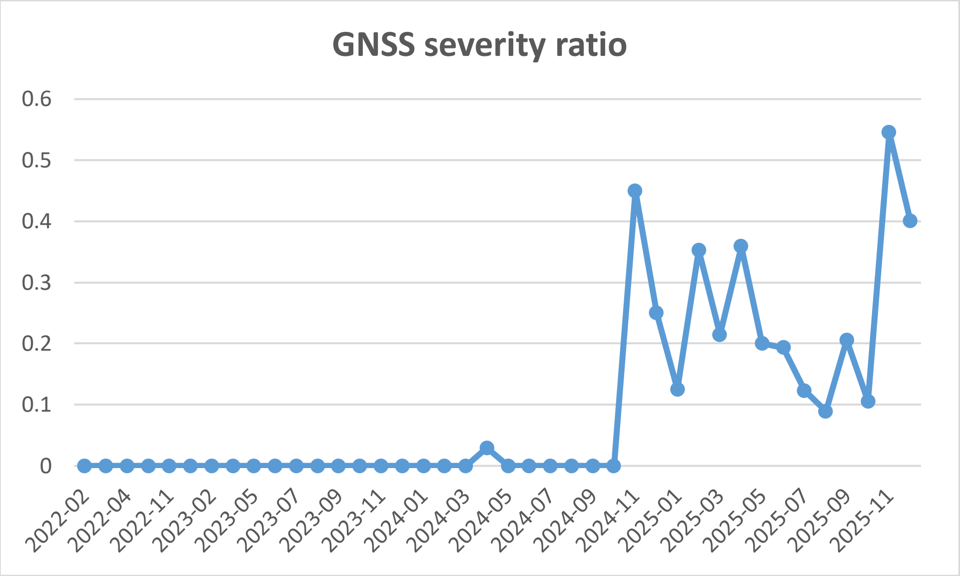


Figure 9. GNSS severity ratio

When *Severity index* and *Severity ratio* are taken together, the patterns suggest that when spoofing became established, GNSS disturbance reports shifted from being dominated by minor anomalies to being increasingly characterized by events with clear operational impact, while the traffic-normalized rate of event was highest during the initial peak and subsequently stabilized to more moderate level. Furthermore, the fact that the months with elevated GNSS severity ratio do not always coincide with the absolute peak of the severity index implies, that in some later periods, even small number of spoofing cases requiring vectors can account for large share of GNSS reports, highlighting that the disturbance profile can remain qualitatively severe even when the absolute frequency of these events per 1000 flights has decreased.

In addition to the severity index and ratio, a separate vectoring rate was calculated as all events involving ATC vectoring per 1000 flights per month, irrespective of whether the disturbance was coded as spoofing or as interference. This is shown in figure 10. The pattern supports the spoofing-based severity indicators by showing that the increase in vectors is visible even when all vectoring events are considered together. The months show clear series of two main and multiple secondary peaks and troughs at lower levels, indicating very similar pattern as the spoofing-based indicators, suggesting that the observed trends are not solely an artefact of whether pilots described the disturbance as “spoofing” or more generally as “interference”.

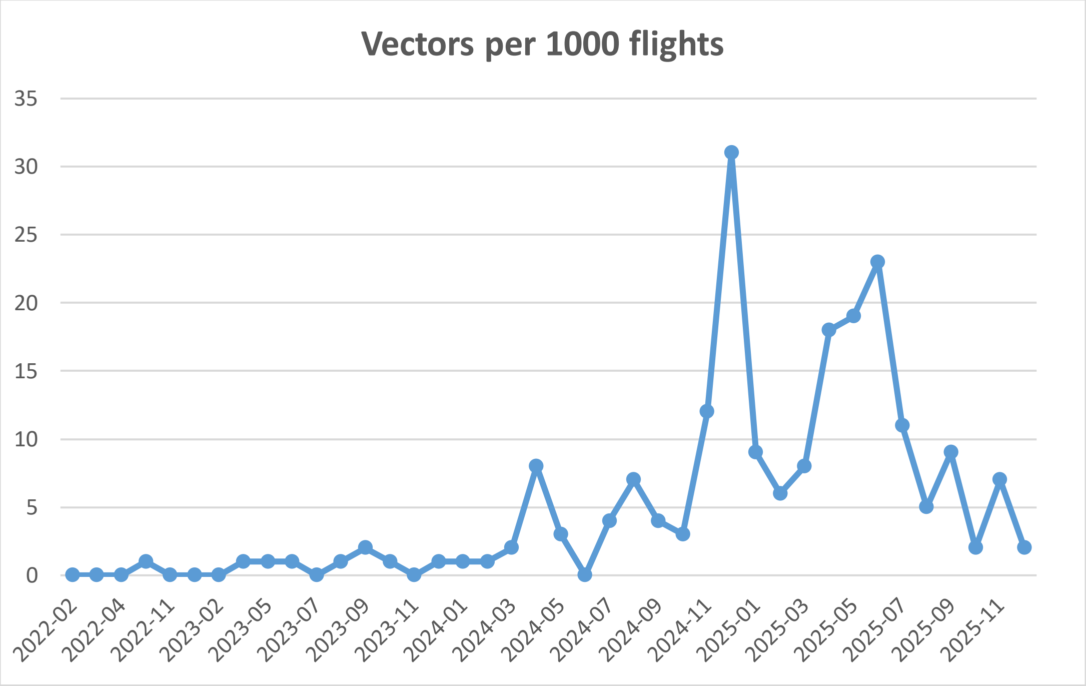


Figure 10. Vectors per 1000 flights

4.2.3 Escalation KPI and BEI

The *escalation* KPI in figure 11 shows the proportion of spoofing reports in each month that involved ATC vectoring. For a long initial period, this ratio remains at zero, reflecting absence of spoofing reports. Once spoofing activity increased in 2024, the escalation KPI exhibits a series of pronounced spikes. In some early exposure months, up to around 0.7-0.9 (70-90%) of the spoofing reports include vectoring, indicating that when spoofing did occur, it very often escalated to a level where crews required ATC support.

As time progresses into late 2024 and 2025, the ratio becomes more variable but appears to fluctuate around more moderate values, often at approximate range of 0.2-0.5 (20-50%), suggesting that during later periods with ongoing spoofing exposure, a smaller share of events escalated into vectoring compared to the earliest peak months. However, the indicator is based on small monthly counts, so even one or two additional vectoring cases can cause visible jumps. Consequently, while plot hints a possible pattern of early high escalation followed by more moderate escalation, this must be interpreted cautiously and cross checked with qualitative accounts on how crews understand and handles spoofing evolving.

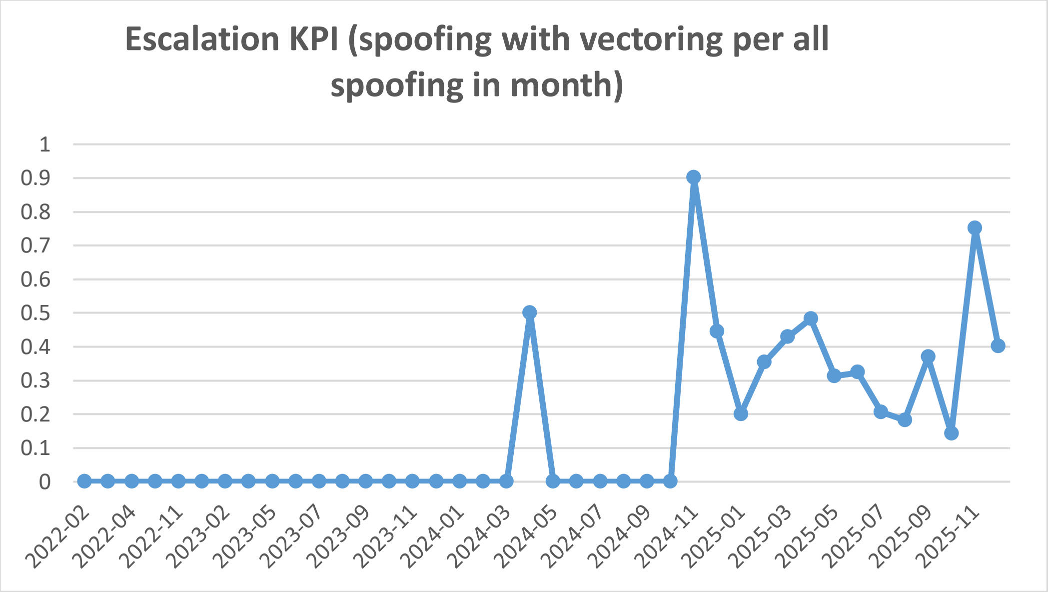


Figure 11. Escalation KPI (spoofing with vectoring per all spoofing in month)

Taken together, the above plots show fairly consistent correlation with the picture, where the barrier and associated learning may have contributed to more effective management of spoofing event over time: as spoofing remained present during the parts of the period, but smaller share of the events escalated to vectoring required. Furthermore, the overall rate of spoofing involving vectoring (Figure 8) decreased after the initial peak, meaning that in combination of declining escalation ratio and reduction in vectors required suggest, that over time crews may have been increasingly able to handle spoofing using onboard procedures and situational awareness rather than relying as frequently on ATC support. At the same time, the fact that the escalation KPI (Figure 11) never falls to zero during the periods of exposure, and that the exposure index (Figure 7) curve shows secondary peaks, indicates that the barrier has not been able to eliminate the need for vectoring and that certain scenarios or contexts continue to challenge its effectiveness.

To strengthen the findings, Pearson correlation between the monthly exposure index and the escalation KPI was calculated as overall correlation of the whole dataset and also as divided into an early phase and a later phase. The results of the correlations are presented in the table 8. Across the full study period, exposure and escalation were strongly positively correlated ($r \approx 0.89$), indicating that months with more spoofing per 1000 flights also tended to have a higher proportion of spoofing events requiring vectors from ATC. When the period was split in March 2025, the correlation was very strong in the early phase ($r \approx 0.93$) and remained positive but somewhat weaker in the later phase ($r \approx 0.75$), suggesting that while escalation continued to increase with exposure throughout, the strength of this relationship decreased slightly over time. This can be seen as consistent with a tentative pattern, where crews and the barrier may have become somewhat more capable of preventing spoofing events even when exposure remained elevated, although the interpretation is constrained by small monthly counts and reporting dependance, introducing multiple limitations for any direct determination of the results, while correlation still remains in relatively high numbers.

Table 8. Results of the correlation

Correlation index	Correlation value (r)
Overall	0,886
Early (by 25-03)	0,928
Late (after 25-03)	0,746

The introduced joint patters of the indicators highlight the importance of viewing barrier performance as a dynamic rather than static, correlating with the findings made by Pitblado et al (2016). Early in the period of increased spoofing exposure, high escalation rations alongside with high spoofing rates may reflect a phase where crews were still unfamiliar with the phenomenon and the barrier, leading to frequent escalation. Later, similar or slightly lower spoofing exposure combined with more moderate escalation ratios and a lower severity rate may reflect adaptation: improved recognition of spoofing cues, more confident usage of the procedure, and better coordination with ATC.

To express the escalation behavior from barrier-centered perspective, a Barrier Effectiveness Index (BEI) was derived from the escalation KPI. BEI is defined as 1-(escalation KPI). For each month, BEI represents the share of spoofing events that were managed without requiring vectors and can be interpreted as an empirical estimate of the probability of success, as defined by Sklet (2006). BEI value of 100 indicates that the barrier performs with 100 percent efficiency, while lower values indicate larger fraction of events escalating to vectors. These values are listed in table 9, BEI as percentage. From an operational perspective, BEI provides practical summary indicator that can be tracked over time to monitor how effective the barrier is. In this research, BEI is used in a comparative sense to highlight temporal changes in barrier performance, rather than to define absolute acceptability thresholds, but it could form the basis for future monitoring targets in the case company’s safety management system.

It must be noted, that in table 9, the dataset includes instances where spoofing counts are zero although vectoring is recorded, arise from the text-mining approach used to classify events. As mentioned in the methods section, spoofing cases were identified using keyword matching in free-text safety reports, leading to cases where reports that describe outcomes without explicitly using the predefined spoofing terms are not coded as spoofing. These mismatches reflect a word-recognition limitation, but not necessarily the absence of spoofing. Furthermore, an additional explanation is that the term “spoofing” became more familiar to pilots only later, as the distinction between interference and spoofing became better understood. Earlier report may therefore have described spoofing symptoms without using the specific term, contributing to under-identification in the keyword-based dataset.

Table 9. Barrier effectiveness index (BEI)

YearMonth	Spoofing	Vectors	Escalation KPI	BEI (%)
2024-05	0	3	0,000	100,0 %
2024-06	0	0	0,053	94,7 %
2024-07	1	4	0,000	100,0 %
2024-08	0	7	0,000	100,0 %
2024-09	0	4	0,000	100,0 %
2024-10	0	3	0,000	100,0 %
2024-11	10	12	0,346	65,4 %
2024-12	36	31	0,593	40,7 %
2025-01	20	9	0,143	85,7 %
2025-02	17	6	0,207	79,3 %
2025-03	7	8	0,100	90,0 %
2025-04	29	18	0,452	54,8 %
2025-05	32	19	0,313	68,7 %
2025-06	34	23	0,333	66,7 %
2025-07	34	11	0,206	79,4 %
2025-08	22	5	0,114	88,6 %
2025-09	19	9	0,194	80,6 %
2025-10	14	2	0,054	94,6 %
2025-11	8	7	0,158	84,2 %
2025-12	5	2	0,051	94,9 %

4.2.4 Hotspots and weekdays

The reporting data also revealed most common areas where GPS interference was detected. This listing is gathered from the descriptions of the reports and shows 5 largest hotspots, presented in figure 12. The listing correlates highly with the qualitative findings and confirms the most critical areas for the barrier's preventative performance. Furthermore, the data was examined to determine whether reporting activity correlated with specific weekdays, but no such pattern was observed as the reports were distributed without clear day-specific concentrations. This supports the interpretation that spoofing behaves as a background risk occurring in broader waves rather than at predictable times or on particular days. The results are presented in table 10.

Table 10. Reporting amounts based on weekday

Weekday	Reports
Sunday	131
Monday	130
Wednesday	122
Saturday	115
Friday	111
Thursday	103
Tuesday	98

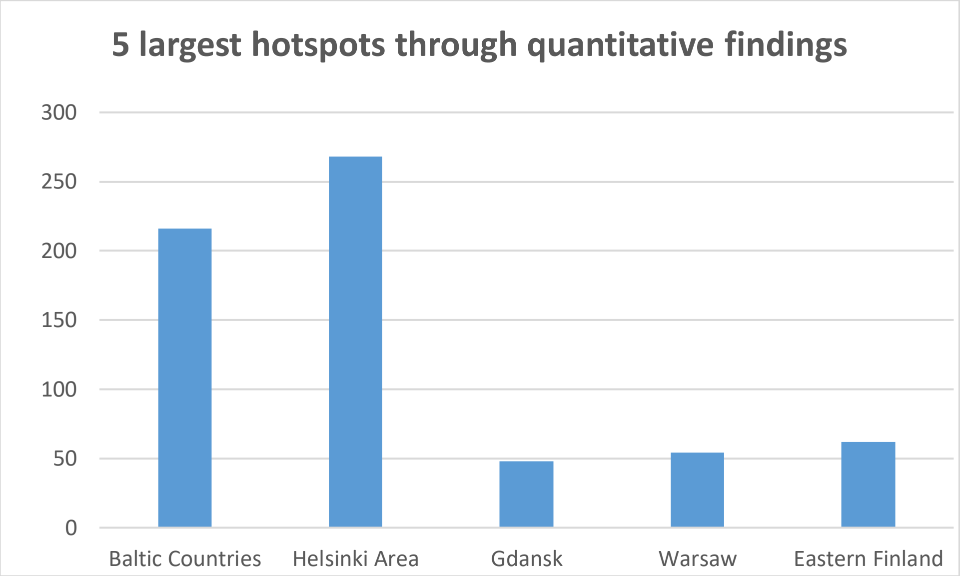


Figure 12. 5 largest hotspots through quantitative findings

4.2.5 Fleet comparison

A comparison of spoofing related vectoring events between the case company's ATR and Embraer fleets shows a distinct difference in escalation patterns that aligns with the procedural differences between the aircraft types. Both fleets experienced a similar initial spike in late 2024 to early 2025, indicating a shared exposure increase during that period. However, the trajectories diverge thereafter. Since the primary aim of this study was to assess the overall effectiveness of the barrier at the organizational level rather than to compare fleets, and to seek for the possible failure modes, the results of the ATR-EMB comparison presented are provided for reference and should be interpreted as descriptive, not deductive, with respect to fleet-level differences.

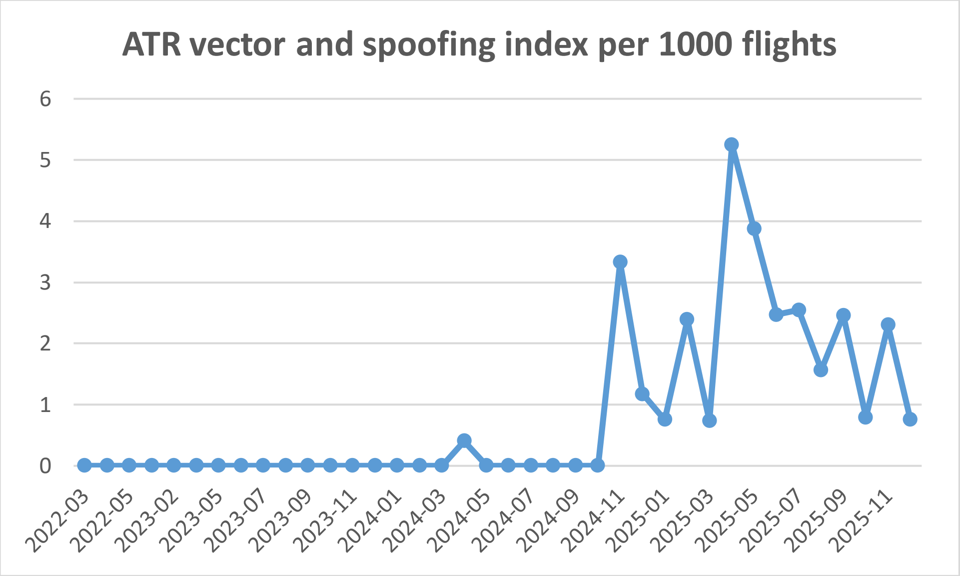


Figure 13. ATR vector and spoofing index per 1000 flights

The ATR fleet, where GPS deselection procedure is applied reactively once spoofing is confirmed, displays recurrent spikes throughout 2025 with several medium and high escalation months, as shown in figure 13. This pattern indicates that spoofing events continued to escalate into situations requiring ATC vectoring multiple times across the year. In contrast, the Embraer fleet, which employs a proactive GPS deselection procedure in one of the most severe known hotspot regions, shows a single major escalation peak followed by a rapid and sustained decline to low or near zero levels, shown in figure 14. After the initial spike, the escalation events remain infrequent with only one clear secondary spike in mid 2025. However, these do not exhibit repeated peaks as seen in ATR data.

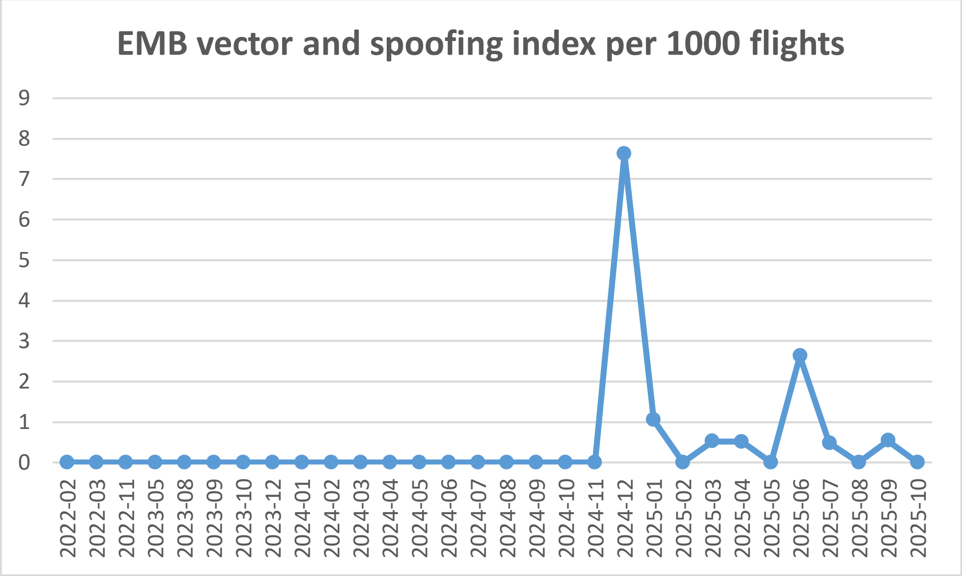


Figure 14. EMB vector and spoofing index per 1000 flights

Overall, the data shows that escalation remains more variable and recurrent in the ATR fleet, whereas the Embraer fleet maintains consistently lower escalation levels after the initial exposure wave. This divergence is consistent with the procedural philosophy, where reactive activation leaves more room for late detection and subsequent escalation, while proactive activation appears to suppress repeated escalation cycles and stabilize performance over time. As the qualitative interviews only focused on ATR pilots, the interpretation of the differences of the fleet is not covered

4.2.6 Limitations

The indicators presented in this section have several limitations that are all important for interpretation. All measures rely on voluntary safety reporting, so under-reporting or shifts in the reporting culture may affect the trends. The escalation-related indicators additionally depend on reporters explicitly describing both spoofing and vectoring in the free-text fields as demonstrated by the table of the keywords. Changing in wording may therefore influence the calculated ratios and affect the number of actual events. Furthermore, monthly event counts, especially for spoofing with vectoring are small, making time-series plot sensitive to any random variation and single cases. None of the indicators directly measure compliance with the barrier procedure and may be influenced by external factors. A change was also made for the company’s reporting procedure in 2024 leading for some changes regarding the requirement for reporting thus lowering number of spoofing incidents, but need for ATC vectoring was kept as mandatory for reporting.

For the reasons mentioned above, quantitative results from the two datasets are interpreted cautiously and complemented by the qualitative interview analysis when drawing conclusions about the barrier performance. It is also important to emphasize that the use of ATC vectors in this study is not interpreted as a negative outcome, but as activation of a secondary safety barrier. The aim is to reduce avoidable dependence on vectoring through more proactive use of procedural barrier and improved pilot support, rather than to eliminate vectoring as a safety measure.

5 Conclusions

This research was set out to examine what is the performance of the barrier mitigating GNSS interference within the bowtie of the case company, and what are the functions affecting it, by answering to the two research question laid down in the introduction:

Research question 1: *How effective is a bowtie-defined procedural safety barrier in mitigating GPS spoofing related risks in regional airline operation?*

Research question 2: *What type of barrier performance modes can be identified from the safety reports and pilot interviews?*

By integrating qualitative interview insights with the quantitate safety reports and indicators, the study provides a comprehensive understanding of how the barrier functions in practice, what constrains its effectiveness, and how the operational environment has changed the adaption of the barrier. The combined evidence shows that while the barrier has strong theoretical and practical potential, its operational reliability is mainly shaped by a dynamic interplay between human, technical, and contextual factors.

Across the interviews, pilots consistently agreed that the barrier is highly effective when used proactively. Once the GPS is deselected in advance of entering known spoofing hotspots, pilots reported nearly 100 percent prevention of adverse outcomes. This finding aligns with the quantitative trends showing decreased escalation ratios during later exposure periods, suggesting that crews increasingly managed spoofing events without relying on ATC vectoring. However, the consistency of this success depends heavily on timely activation. Spoofing was often described throughout the interviews as subtle, gradually emerging, and hard to detect early without any concrete signs, making proactive usage essential. If the detection is delayed, the widow for the effective barrier activation narrows quickly, reducing its value as a preventative defense.

The major limitations of the barrier identified in the research arose from human performance factors rather than the procedure itself. Habituation, normalization of deviance, and declining vigilance emerged as extensive themes throughout the interviews. Pilots described interference as routine, no longer triggering immediate suspicion, leading to delayed or skipped activation even in well-known and recognized hotspot regions. This desensitization can be seen as directly undermining the barrier’s preventative functions. Additionally, as the procedure relies heavily on memory and individual judgment, it makes the performance of the barrier vulnerable for distraction, workload, and differences in individual operating styles. These factors explain the variability in barrier use and can be protected to the monthly fluctuations observed in vectoring cases within the quantitative data. Even though crews have been able to improve their recognition towards the spoofing and show gained experience, the reliance on human memory and attention continue to introduce inconsistency into when and how barrier is applied.

Detection and response time formed a second major reason for performance degradation. Interviews revealed that pilots often notice spoofing only after its effects have already begun to influence navigation accuracy. The spoofing effects can progress faster than pilots can diagnose the issue and apply the procedure required, especially in high workload phases of flights. This lag helps explain the early spikes in quantitative escalation rations during the first major exposure wave, as crews encountered rapid anomalies with limited prior experience and anticipatory use of the procedure. Although later periods saw lower escalation ratios, detection related delays remained persistent operational challenge.

Furthermore, technical and environmental limitations influence barrier performance, though to a lesser extent than human factors. The availability and performance of alternate navigation systems such as DME/DME and ATC radar vectoring shape how dependable the barrier is once the GPS is deselected. Pilots expressed that while such limitations are relatively uncommon, these can reduce the barrier’s reliability in specific regions or circumstances. These constraints contribute to the continued presence of vectoring cases in the quantitative data, despite the improved familiarity and more widespread use of the barrier, although the coverage and availability of the alternative navigation systems was reported to be good according to the pilots, reducing the effect of degradation factor of the environmental limitations.

The quantitative indicators confirm that GPS spoofing has evolved into a wave-like, operationally significant risk rather than a stable background noise. Exposure, severity, and vectoring KPI's show a marked increase in spoofing reports and in events requiring vectoring after 2024, followed by periods of partial stabilization. Normalizing events by traffic volume and examining GNSS severity ratio reveals, that when spoofing is active, a substantial share of GNSS disturbances are operationally consequential, sometimes with nearly half of the reports involving spoofing requiring vectoring. The escalation KPI and derived Barrier Effectiveness Index (BEI) suggest, that over time, a somewhat smaller proportion of spoofing events escalate to vectoring even when the exposure remains elevated. This hints of adaption in crew handling and barrier use, although the interpretation is constrained by small monthly counts, reporting dependence, and changes in reporting procedures. Fleet-level descriptive plots further indicate that a more proactive procedural philosophy in the Embraer fleet is associated with a simple major escalation peak, followed by sustained low levels, whereas the more reactive ATR usage pattern shows recurrent spikes, though these differences are not analyzed statistically. However, this dynamic nature of exposure shows, that the barriers performance must be understood as equally dynamic, varying with both operational threats and human adaptation, and confirms that it should be evaluated using both quantitative and qualitative methods as shown by Pitblado et al (2016), to thoroughly understand the reasons behind the data.

Taken together, the integrated evidence provides us the possibility to answers to the research questions. For the first question *"How effective is a bowtie-defined procedural safety barrier in mitigating GPS spoofing related risk in regional airline operation"* the evidence shows that the barrier is capable of delivering very high levels of protection when applied proactively and under alternative navigation infrastructure. By actions taken before entering the known hotspots, majority of the negative outcomes can be prevented. However, the findings conclude that the effectiveness is not constant, as it is diminished by delayed detection, habituation, and situational workload, meaning its full potential is not always realized. Thus, barrier is highly effective in principle but variably effective in practice, as demonstrated using indicators such as BEI.

For the second research question *"What type of barrier performance modes can be identified from the safety reports and pilot interviews following the implementation of the barrier"* the interviews revealed several distinct performance modes, which are presented in a fishbone diagram in figure 15. These modes directly correspond to the variability observed in quantitative indicators, such as fluctuating vectoring rates and changing escalation patterns over time. Together, the data identified consistent and recurring modes in which the barrier either functions as intended, becomes partially effective, or is undermined by human or technical factors.

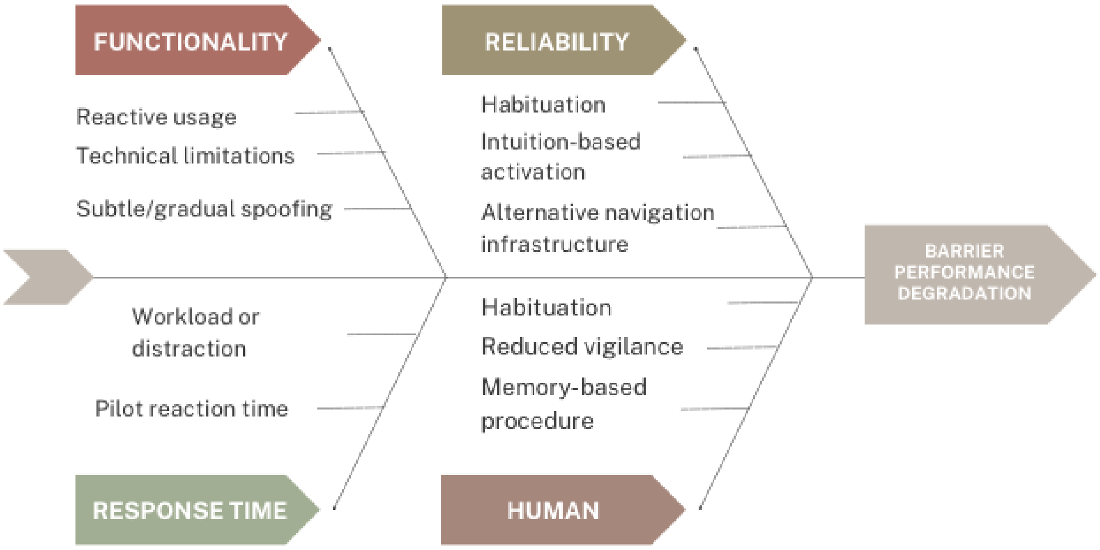


Figure 15. Fishbone diagram of performance degradation modes observed during the research

The research opens multiple possibilities for further study related to the performance of the barriers, particularly regarding the use of AI to detect patterns in performance monitoring data. The Barrier Effectiveness Index developed in this study illustrates how escalation in reported events can be transformed into a practical monitoring metric, but it should be refined and compared using normalized rates, confidence intervals, and more comprehensive datasets. As the underlying data in this research is relatively shallow and sensitive to reporting practices, further work on standardizing safety report structures, especially for similar spoofing and vectoring events, would improve parameter recognition and reduce misclassification, further strengthening any AI-supported analytics.

Previous research by Durieux et al. (2025) indicates, that the pilot experience only marginally increases the confidence in GPS and that detailed knowledge of spoofing cues remains limited across experience levels, highlighting the need for targeted training that addresses GPS vulnerabilities, cognitive biases, and uncertainty management in atypical scenarios. Given that the habituation towards GNSS interference was a very common theme across pilot interviews in this research, emphasizing this, and the one's highlighted by Durieux et al. (2025), explicitly in trainings such as Crew Resource Management (CRM), is recommended for crews to recognize normalization of deviance as a risk factor rather than as background noise, increasing the likelihood for crews to better recognize and to act to animalities of GNSS interference, but also increasing the understanding of the effects it may lead to. In addition, because the current deselection process relies heavily on human memory, further measures to reduce this dependency should be considered. These could include revising checklist and defining clearer more straightforward activation criteria for the procedure, particularly for the ATR fleet.

Future GNSS interference patterns will largely depend on the evolution of global geopolitical conflicts, which currently show a strong correlation with interference activity. The present conflicts have exposed significant vulnerabilities in GNSS-based operations, while simultaneously underscoring the critical importance of alternative navigation systems for aviation and opening possibilities for future technical development within the industry. As global uncertainties evolve, they will shape the requirements for bowtie’s safety barriers and the conditions under which these should be activated. In this context, such barriers may be most effective when designed as conditional “activate-when-necessary” controls, triggered by predefined indicators, such as the proposed BEI, once exceeding specified thresholds, enabling relatively simple implementation across fleets once the global situation stabilizes.

Although the current geopolitical environment has generated substantial concerns related to delays, safety, and operational costs, it has also provided an important drive for organizational learning. In particular, systematic use of operational safety reports has demonstrated how data-driven learning can sustain safe and resilient operations under heightened uncertainty.

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Appendices

Appendix 1. Semi-structured interview questions (Finnish)

Functionality / Effectiveness

1. **Kerro omin sanoin mitä GPS navigoinnin pois ottamisella kriittisillä alueilla pyritään saavuttamaan, ja milloin sitä pitäisi soveltaa**

2. **Milloin olet viimeksi käyttänyt kyseistä menettelyä? Missä?**

3. **Onko esimerkkiä tilanteesta, jossa menettely ei toiminut hyvin tai ollenkaan?**

4. **Koetko, että menettely on tehokasta GPS spoofingia vastaan?**

Reliability / Availability

5. **Kuinka nopeasti koet pystyväsi tunnistamaan GPS spoofingiin liittyvän tilanteen, ja siirtymään menettelyn mukaiseen toimintaan? Mitkä tekijä helpottavat, mitkä vaikeuttavat?**

6. **Onko selvää missä vaiheessa otat suojauksen käyttöön vai onko se sattumanvaraista/reaktiivista?**

Response time

7. **Kuvaile miten yleensä toimit, kun huomaat GPS spoofingin? Ehditäänkö menettely ottaa käyttöön vielä tämänkin jälkeen?**

8. **Vaikuttaako lennonvaihe menettelyn käyttöönottoon?**

Human performance

9. **Vastaavatko ohjeistukset mielestäsi lennolla toteutettuja menetelmiä? Koetko olevasi turtunut GPS häirintään?**

Appendix 2. Semi-structured interview questions (English)

Functionality / Effectiveness

1. **In your own words, what is the objective of disabling GPS navigation in critical areas, and when should it be applied?**

2. **When was the last time you used this procedure? Where?**

3. **Do you have an example of a situation where the procedure did not work well or did not work at all?**

4. **Do you feel that the procedure is effective against GPS spoofing?**

Reliability / Availability

5. **How quickly do you feel that you are able to recognize a GPS spoofing situation and transition to the prescribed procedure? What factors make this easier or more difficult?**

6. **Is it clear at what point you should activate the protection, or is it more random/reactive?**

Response time

7. **Describe how you typically act when you detect GPPS spoofing. Is there still enough time to implement the procedure after detection?**

8. **Does the phase of flight affect the implementation of the procedure?**

Human performance

9. **In your opinion, do the instructions correspond to the procedures actually carried out during flight? Do you feel desensitized to GPS interference?**