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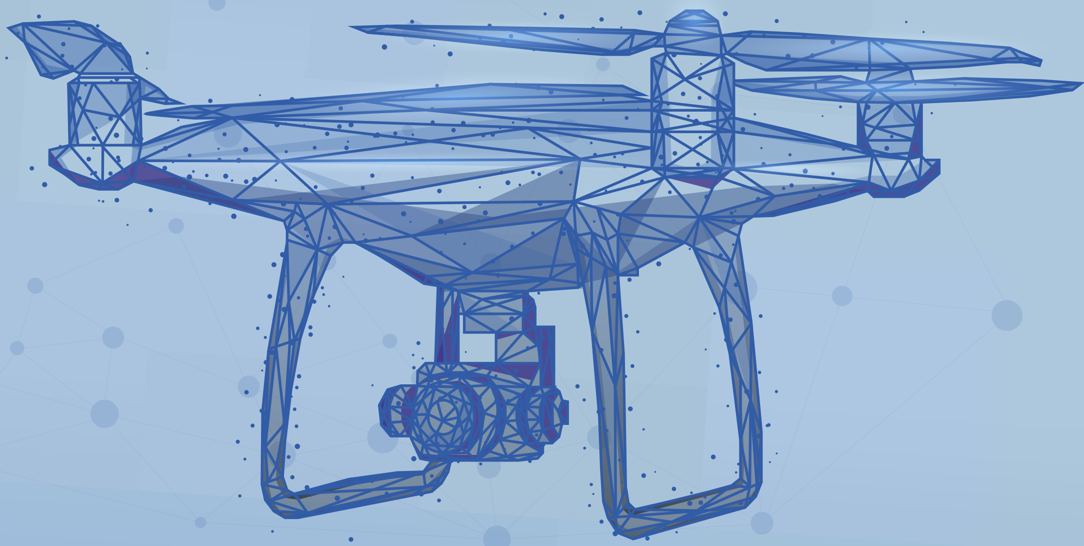

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Research Article

A Solution Package for Rules and Regulations of Unmanned Aerial Vehicles

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Abstract

Since the Paris Agreement of 1919, the world witnessed a lot of changes in terms of airspace utilization. Today, airspace utilization is problematic for practitioners and theoreticians with new developments and innovations such as VTOL (Vertical Take-Off and Landing) aircraft and sudden changes in the international context because of wars and conflicts. In this paper, it is aimed in essence the development of airspace utilization one more step forward in parallel with the technological pace. To reach this purpose, the most controversial vehicles, UAVs (Unmanned Aerial Vehicles), are examined depending on their utilization in civil aviation and airspace. The concept of governmentality and its roots are also used for the development of a legal basis for UAVs. Comparative law methodology is selected as a research model. According to the findings, there is still room for legal development of UAVs, especially regarding security and international politics because of the different utilization of different nations. At the end of the article, it reached a frank conclusion that civil aviation needs rules and regulations in a wide and international sense for these vehicles. New policy offers and titles are organized for these vehicles like the Annex of ICAO (International Civil Aviation Organization).

Keywords

Comparative Law and Legal Studies
Governmentality
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1. Introduction

It is a sound, strict and comprehensively accepted reality that the First World War was such a destructive event that millions of people died, thousands of households were scattered, and national borders and, maybe, nations were re-defined. On the other side, it is another reality that wars, especially big ones, had dramatic impacts on concrete and abstract technologies. For example, developing technologies and army designs such as in the Thermopylae War, the Conquering of Constantinople, the Battle of Kadesh, and the Invasions of Chengiz Khan and Alexander the Great. Similarly, the First World War was the main cause of the distinction between the two realities in terms of civil and military aviation with the Paris Agreement of 1919. With this agreement, it became an important step that the absolute utilization rights of airspaces over national borders, territories and territorial waters were given to the states by international order. Since then, the aviation economy and politics have been in the hands of the states and they are sustained with different mechanisms under the names of civil aviation and military aviation due to the politics of states.

Unmanned Aerial Vehicles (UAVs) are one of the fruits of technological development with the understanding of hybrid sciences. They can be utilized in almost every economic and instinctual activity of humankind. Although they have special advantages for their versatile nature, De Garmo (2004) insists on their negativeness in terms of arrangements in the safety and security laws, rules and regulations depending on their dependence on

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a highly technological development nature. This nature has grown up with newer and specific techniques and concepts such as path length, optimality, completeness, cost-efficiency, time efficiency, energy efficiency, robustness and collision avoidance (Aggarwal and Kumar, 2019). This impact can easily be observed in the paper of Urbahs and Jonaite (2013) on agriculture applications and it can be concluded that UAVs can be re-arrangeable due to utilization purposes. For example, Eisenbeiss (2004) discusses their dimensions in a technological language in the field of photography but this can also an intelligence matter on a wide and state spectrum. According to Elmeseiry et al. (2021), UAVs have still challenges with flying smoothly and other fields including collision avoidance, battery life and intruders such as burglars. With their economic and political explanations, Fuhrmann and Horowitz (2017) maintained that states can create their autocracies and democracies over UAVs technologies that have great importance on supply-side factors. In light of this argument, shortly, it will try to answer in the paper the question of "How can we develop a new way of UAVs' governance in terms of security and safety depending on laws, rules and regulations under the assumptions of no environmental and noise risk?"

While we analyze this question, we will benefit from law and social sciences methods such as comparative law methodology with the help of the Annex of ICAO (International Civil Aviation Organization), because of their legislative power in civil aviation. One of the purposes of the research is to examine the philosophical roots of Annex or current rules and regulations and the law systems of aviation benefiting from the "Governmentality" concept of Foucault. Secondly, it is aimed to develop a detailed legal framework for UAEs in terms of security and safety benefiting from law and social sciences methodologies.

For Foucault (1977, 1981, 1985, 1988, 1997, 2000), the power of governance' exercises take their roots from the definition, identification and classification of society and individuals one by one. When it realizes this first step, it utilizes surveillance mechanisms such as prison, formal education and training etc. If a deviation occurs both in society and individuals; specific, known and rational tools, habits, mechanisms and reflexes such as punishment and discipline and in some situations, semi-medical mechanisms such as psychoanalysis are utilized. In specific considerations and context, also some deviations are created by the hands of governance in person. Bröckling (2001) describes this mechanism as military obedience which is the utmost form of discipline and it includes sexual, social, and psychological motives, patterns and designs, besides these, it does not aim only to change behaviours, but also change daily and even momentary reflexes. If it is concentrated on aviation activities, it shall be sure that some activities such as communication, leadership or occupational health and safety are ensured with a great amount of attention that needs extra effort and can consume the emotions and cognitive powers of aviators. Therefore, individuals need to gain extra capabilities and abilities for before-after awareness and readiness through aviation governmentality. So discipline, punishments and other factors are so important like the creation of military obedience. It's the essence of modern working and business activities.

But, in the UAV context, the situation is so different depending on the relatively lesser number of human resources. Security has priority, therefore, the protection of private and state property rights can be very important. In this work, this subject is the main focal point of our research. By doing so, research completes a legal gap between practice and theory on UAV technologies philosophically and scientifically.

In light of the arguments above, in the first stage of the research, a wide literature review of the research will be realized and then a comprehensive methodology takes its place in the second section. Findings and discussions, conclusions and policy implications will be the subjects of our next step and finalization of this research.

2. Literature Review

As it is stated in the methodology and theory development section, law and legal studies and social sciences can be utilized under one umbrella. As it is stated in UAV literature, these technologies suffer from legislative power in terms of security and safety. It will be developed a framework in light of the methodology and theory development in this section. Out of their utilization as air vehicles and engineering designs, this literature review mainly contributes to our theory of aviation security and safety.

UAVS are highly technological vehicles that mainly have greater maneuverability, low risk to human operators, significant weight savings, lower costs, the potential for superior coordination, and opportunities for new operational paradigms, for these reasons, they can be utilized for intelligence, surveillance, and reconnaissance; communication relay or gateway; radar jamming and decoying; suppression of enemy air defence (SEAD) missions; theatre and cruise missile defence; fixed and moving target attack; and air-to-air combat in military aviation (McLain et al., 2000). Tahir et al. (2019) classify their purposes in civil aviation as monitoring, surveillance, marketing, mapping, business and management, security, hobby, research and delivery logistics, and photography. Doherty et al. (2000) underline problems in fully autonomous UAV utilization such as negative weather conditions and cold regions (also in Gaffey and Bjardwaj, 2020) limited energy, capacity and hardware and software problems (Chao, 2010). Otto et al. (2018) maintain that UAVs or drone technology are utilizable for innovations in operational optimization opportunities. Besides these developments, they are open to new technologies such as the Internet of Things, machine-type communication, data processing Motlagh et al. (2016) and upper-class remote sensing (Pajares, 2015) of which negative impacts are unknown or unpredicted in terms of aviation safety and security.

Coifman et al. (2006 a,b), Puri (2005) and Wang et al. (2016) describe their features as monitoring tools of air traffic for surveillance purposes in city developers' programs. Anderson and Gaston (2013) examine the importance of UAV utilization for ecological purposes and small ecological lands. Jones et al. (2006) determine their same impacts on wildlife research and life. For Klemas (2015), UAVs are utilizable for coastal and environmental remote sensing. Herwitz et al. (2004) describe the utilization of UAVs for agricultural surveillance and decision support. Kim et al. (2019) also maintain that the impacts of the UAVs on the facilitation of business in the agriculture sector continue especially in specific processes such as pesticide and fertilizer spraying, seed sowing, and evaluation of plant growth.

He et al. (2017) underline UAV's deficits in communication security. According to Coutinho et al. (2018) depending on their complex electronic infrastructure, UAVs are problematic for airspace utilization, although they have wide and comprehensive utilization fields. Also, Cai et al. (2014) state that airspace utilization is a big problem for civil aviation, for them, although states such as the USA (United States of America) and Australia try to develop specific regional and national arrangements for the utilization of airspace, an international arrangement is not possible. For Hardin and Jensen (2011), the main purpose of the USA is to regulate UAVs is to order commercial and private air travel depending on UAV dense use within the border of the USA. Fuhrmann and Horowitz (2017) also state that UAVs are one of the great security threads for countries.

Like many other utilization purposes, it is still a big debate over whether these technologies are humanitarian, especially in military activities. For example, Kreps (2014) states that UAVs' efficient and effective utilization in interventions by the USA in Pakistan, Somalia and Yemen in taking military actions, but they are criticized in terms of legal and ethical sides by authorities. Kreps and Kaag (2012) also maintain their negativities in military utilization. These problems are directly related to military and international law and politics. If it is returned to civil aviation problems, Shresta (2021) draws attention to civil UAV utilization purposes and states that the aviation world will be witnesses some problems with UAV-related traffic management in the next years, in terms of surveillance, navigation and communication. For Zuo (2022), controlling these vehicles in the airspace is arguable and open to development depending on their sophisticated design, despite the intensive economic demand of the public. Lin (2018) and Zeng et al. (2016) underline communication deficits and technologies that can be used against them in the complex structure of UAVs. Shakhatreh et al. (2019) argue the negative impacts of UAV's civil infrastructure and architecture structure on the ground services and operations, they count the challenges as charging challenges, collision avoidance and swarming challenges, and networking and security-related challenges.

Governmentality, on the other side, is a degree of management or government practices. However, it is a specific state, which includes psychological, sociological and economic motives, awareness and readiness to govern or to be governed. According to Skalen's (2006) contribution, it also examines some ethical investigations on governed-governing relationships in terms of know-what, know-how and know-who sides, therefore it focuses on a productive knowledge-force mutualism. Ferguson and Gupta (2002) examine some extra and important mechanisms in the development stages of governmentality such as discourses, norms, identities; self-regulation and techniques for the disciplining and care of the self and political economy. However, Clegg (2019) underlines the impacts of culture and cultural designs on government practices and mechanisms, because of their definitive impacts on governing and governed relationships. Besides, according to Collier (2009), it can be maintained that governmentality is to make thinkable and practicable of an activity for governed and governing. Li (2007) avoids the concept of governmentality and utilizes governmental interventions in some considerations such as natural disasters (floods, droughts, accidents and diseases), excessive economic price movements of commodities in international markets and media relations. Larner and Walters (2004) emphasize that governmentality is important for global wealth, justice and welfare, therefore it is a global matter.

3. Method

Before the ICAO decides on a specific event, incident or accident on the decision-making side or joins a legislative action in terms of civil aviation, generally moves depending on its standards which are accepted by member countries. Therefore, these standards are legally binding and known as ICAO Annexes. Depending on the legislative force of ICAO, a comparative law methodology will be utilized in this research. This research method develops under the impacts of social sciences and law and legal studies. Besides these, the law includes different reasonings such as the a priori or metaphysical method, the analytical method, the historical method and the comparative method and the comparative method serves to a better understanding between the influential and active spirits of different nations as well as for the unification of the commercial laws of the world (Scmitthoff, 1939). Feeley (1976) investigates the importance of law in social sciences. According to his findings, the rationality between legal studies and social studies or a separate theory of law and society will be abolished. Besides these, Garth (1998) pays attention to some examples such as racial discrimination, poverty and crime, and underlines the forces of competition and cooperation of law legal sciences and social sciences. Nevertheless, Twining (2005) maintains that comparative legal and law studies suffer from necessary attention in social sciences like sociology under the conditions of state-based legal arrangement, modernization, technological development and attitude changes in the developing world. For Samuel (2009) this situation is also correct and interdisciplinary research is a need. Interdisciplinary research, for example. According to Villegas (2006), is nothing more than restructuring Bourdieu's structuralism, which accepts human behaviours in the mental structures or schemes, to make comparisons between American and French legal fields. Nonetheless, Ratner and Slaughter (1999) investigate the variants and objectivity of international law and prescribe its decision-making process depending on their reasonings and logic, especially in event studies like "dirty wars and events" such as the Bosnia War of 1992. For Samuel (2008), with all of its dimensions and legal constructs such as economic, political, social (and cultural) and psychological, comparative law should be accepted as a different branch of social sciences. On the other side, Faigman (1989) states that social sciences with all of their deep explanations of human behaviour can be accepted as only modest assistance to legal studies and this modesty can change depending on the quality of social science research. Under this specific literature review on legal studies and social sciences, a comparative law methodology is selected as a research methodology in this research, if it is concentrated on the details.

Before this work, there were also some other studies in transportation literature with different methodologies, for example, Ojo (2019) developed a classification methodology, and Mokhtarian (2009) underlined the importance of transportation schemas and tables. Auld and Mohammadian (2009) developed a simulation model after an intensive and dense literature review. According to Reitz (1998), i) Explicit comparisons diminish ambiguity in the law and legal studies, ii) They depend on similarities and differences among the legal systems and consider functional equivalence, iii) They are aware of distinctive characteristics of the individual legal system and commonalities concerning how the law deals with the particular subject under study, iv) The main aim of comparative analysis is to make more wide levels of abstraction through its investigation of functional equivalence, v) The comparative method invests cultures, similarities and differences among legal systems into the analysis, vi) It fills the gap between practice and theory, and also different systems. Meares (2014) offers a new framework that includes social sciences and law to increase the power of law against crime. Cook (1927) describes and emphasizes the concept of "syllogism" in the law study-making process. Besides these, Hill (1989) underlines that three important legal systems in the world law conjuncture are Germanic, Romanistic and Anglo-American legal systems. Therefore, different legal applications gain different insights with explicit comparisons (Schlesinger, 1995). And for this cause, comparative law is a sociology of law (Kamba, 1974).

4. Results and Discussion

According to our main findings, if it is realized a comparison between UAVs and other aircraft, it is natural to find important differences beginning from their utilization purpose, economic and business organizations, and safety and security understandings in terms of civil aviation and aviation and international law and legal dimensions. This research, it will try to develop a framework focusing on these clear and net differences benefiting from governmentality and technological abilities, capabilities and deficits of UAVs. Also, Stöcker et al. (2017) underline the importance of a clearer legal system and framework with market forces such as industry design standards and reliable information about UAVs.

It is clear that the structure of UAVs is relatively more micro dimensions, are suitable without human or crew transportation but ground operations and services, require innovative infrastructures and aerodromes, clearly more open to high technologic activities and arrangements. These features carry it directly to the focus points of governmentality subjects with great rationality. For example, if it is concentrated on Weidner (2009) who describes these subjects or problems as the European Union, the integrated region, globalization, global civil society, development economics, security, the failed stated, peacebuilding and peacekeeping, immigration, refugees, AIDS (Acquired Immune Deficiency Syndrome), humanitarian need, the environment, global health. The main features of these problems that are directly related to global order, are new or relatively new, change their position depending on time, space and extension and are subject to different scientifical branches like UAVs. According to Elden (2007), the main efforts of the governmentality mechanisms are purposed to optimal efficiency and effectiveness in the fields of society, economy, population, security and liberty, and geographical-territory dependence gain importance in all these issues. Essentially, the importance of geographical territory is the main problem of air transportation since the Paris Agreement of 1919 on which the sovereignty of the state over airspace was accepted. Neu and Heincke (2004) investigate whether governmentality mechanisms and applications have some borders, according to them financial anxieties have negative impacts on governmentality aims.

As it is understood, humankind needs governmentality in deviations from normal, it has borders and it needs law and legal power greatly. It is directly related to psychological and bio-readiness and awareness of people. Especially, in this technological and innovative age, it is one of the first steps to gain consciousness toward new or relatively newer. Therefore, a comparison between UAVs and normal civil aircraft with all their dimensions is suitable. For example, in accidents, damage and injury caused by UAVs (Cracknell, 2017), in excessive utilization of airspace with drones or UAVs as in India (Srivastava et al., 2020) or anywhere (Kubas, 2023).

5. Conclusions

After the COVID-19 disease, civil aviation began to change its core, sustainability, unmanned systems and technological development in every section of civil aviation. It has witnessed many different inventions and innovations with all of their negative impacts. On the other side, unmanned aerial vehicles are financially accessible to people. There are no strict aerodrome rules and regulations about them, navigation, surveillance and communication can be realized easily with them within the airspace. Standardization levels in terms of certification and licensing are lower than other air vehicles. However, as it is stated in the literature review, they can easily be utilized for military purposes with specific technological arrangements. They are open to malevolent activities such as terrorism, ultra-excessive nationalism, burglars, smuggling, and contravention of state and private rights. Civil aviation management overcomes all of the other negativities through its special governmentality, especially after the Chicago Convention of 1944. In clearer words, Civil Aviators and stakeholders from all of the civil branches have consciousness, awareness and readiness towards negativities in their occupation through the forces of intensive training and education activities and licensing and certification processes, so governmentality according to the literature review of this research. But, unmanned aerial vehicles even devices are open to discussion.

6. Policy Implications

Especially, more strict rules, and regulations should be developed in a set of standards like Annex understanding of ICAO for UAVs on an international basis by stakeholder and civil aviators. Because of licensing and certification processes, education and training need extra care and details. Besides psychological awareness and readiness, literacy of law and legal side, technical details, aerodrome, air traffic and airspace utilization, the consciousness toward accidents incidents and risks is still ambiguous. In this paper, governmentality with all its dimensions and mechanisms can be considered the first step, with all of its power on destructive, definitive and re-definitive roots on the act of governed and governing. Standardization and legislation should be the second stage of these efforts in the field of Unmanned Aerial Vehicles with definitions and descriptions, numerical details, warnings and cautions such as IFR (Instrument Flight Rules) and VFR (Visual Flight Rules) rules, and extraordinary events such as wars, international conflicts between states and volcanic eruptions. These standards should be comprehensive, flexible and organic in light of comparative law.

Nomenclature

AIDS	: Acquired Immune Deficiency Syndrome
ICAO	: International Civil Aviation Organization
IFR	: Instrument Flight Rules
SEAD	: Suppression of Enemy Air Defence
UAV	: Unmanned Aerial Vehicle
USA	: United States of America
VFR	: Visual Flight Rules
VTOL	: Vertical Take-Off and Landing

CRediT Author Statement

Olcay Ölçen: All dimensions of the research are conducted by Olcay Ölçen.

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Research Article

Exploring the Dynamics of Perceived Value, Brand Image, and eWOM: a Path to Loyalty in Vietnam's Low-Cost Airline Industry

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Abstract

This study investigates the key drivers of passenger loyalty within Vietnam's low-cost airline sector, focusing on the roles of perceived value, brand image, and electronic word of mouth (eWOM). Customer loyalty, a crucial factor in the long-term success of airlines, enables cost efficiency, enhances brand equity, and builds sustainable customer relationships. Drawing on Holbrook's Consumer Value Theory and Social Exchange Theory, the research posits that perceived value influences both loyalty and eWOM directly, while brand image moderates the eWOM-loyalty relationship. Using a structured survey, data was collected from 236 passengers, and Structural Equation Modeling (SEM) with SmartPLS 4.0 validated the measurement and structural models. Findings reveal that perceived value significantly enhances brand image and loyalty and drives eWOM, supporting its role as a core component of passenger behavior. Additionally, the moderating role of brand image strengthens the impact of eWOM on loyalty, indicating that a robust brand image reinforces consumer trust and engagement. The study's practical implications recommend that Vietnam's low-cost airlines prioritize perceived value, actively manage eWOM, and invest in brand-building strategies to boost loyalty. While these insights offer a comprehensive framework for strengthening competitive advantage, future research should address the study's limitations by expanding the sample to different regions and exploring additional factors, such as service personalization and environmental sustainability. This research thus provides both theoretical contributions and actionable guidance for enhancing passenger loyalty in low-cost airlines.

Keywords

Airline Brand Image
eWOM
Low-cost Airlines
Passenger Loyalty
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1. Introduction

Customer loyalty is a pivotal factor in the long-term success of airlines, offering significant economic benefits and competitive advantages. Research into customer loyalty provides airlines with invaluable insights for enhancing cost efficiency, bolstering brand equity, and establishing sustainable, long-term relationships with customers. Retaining loyal customers is not only more cost-effective than acquiring new ones, but these customers also tend to increase their purchase frequency and volume, leading to substantial economic gains (Arslan, 2020).

Furthermore, customer loyalty plays a key role in enhancing brand equity. A strong brand helps airlines differentiate themselves in markets where services are

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often perceived as homogeneous (Denoue & Saykiewicz, 2009). This differentiation is crucial for maintaining a competitive edge. Airlines that foster customer loyalty can strengthen their market position by building enduring relationships with customers. Such relationships not only secure a steady stream of revenue but also turn customers into advocates who promote the brand and attract new customers at a lower cost (Arslan, 2020)

However, most existing research on customer loyalty in the airline industry has primarily focused on traditional factors like service quality and perceived value, while overlooking the combined impact of personal values, destination image, and electronic word of mouth (eWOM) on customer loyalty. In addition, while several studies have emphasized the impact of brand image on customer loyalty (Fu, 2023; Kudeshia & Kumar, 2017; Yodpram & Intalar, 2020), limited research has explored the moderating role of brand image in the relationship between eWOM and customer loyalty. eWOM has become a powerful tool for shaping brand perception and fostering customer engagement (Saa'ed & Saa'ed, 2024), making it critical for airlines to understand how brand image moderates this relationship, especially in the digital age.

Vietnam's air transportation market is experiencing rapid growth, driven by rising tourism and a growing middle class. The country hosts five key airlines: Vietnam Airlines, VietJet Air, Bamboo Airways, Pacific Airlines, and Vietravel Airlines. Among them, VietJet Air and Pacific Airlines are the primary low-cost carriers (LCCs). These airlines collectively serve over 116 million passengers annually 2023, with LCCs accounting for over 60% of domestic traffic. VietJet Air leads the market with extensive domestic and international routes, while Pacific Airlines focuses on affordable domestic services for budget-conscious travelers (JSC, 2022).

This competitive landscape highlights the surging demand for affordable air travel and underscores the vital role of customer loyalty and brand image in sustaining growth. This study aims to address these gaps by examining the relationships between personal values, destination image, eWOM, and customer loyalty, with a particular focus on the moderating effect of brand image. By doing so, the findings will provide both theoretical contributions and practical insights that can enhance marketing strategies in Vietnam's LCC market and beyond.

Perceived Value

Perceived value in aviation is the balance between the benefits passengers receive and the sacrifices they make. Benefits include service quality, brand reputation, and customer satisfaction, while sacrifices encompass monetary costs and non-monetary factors such as time and effort (Lu, 2014; Mayr & Zins, 2012). Key service attributes like refund policies and baggage allowances directly influence perceived value, shaping passengers' pricing perceptions and overall experience (Fragnière et al., 2012).

Brand image plays a critical role in enhancing perceived value, fostering customer loyalty whether the airline is full-service or low-cost (Fu, 2023). Additionally, service quality and price fairness are pivotal in passengers' evaluations, with non-monetary costs like time and effort also impacting value perception (Lu, 2014). Airlines can strategically boost perceived value by aligning service offerings with customer expectations and employing value-based pricing models (Zhang et al., 2014). Corporate Social Responsibility (CSR) initiatives further elevate perceived value by strengthening brand image and loyalty (Mohamed, 2023)

Consumer Value Theory, developed primarily by Holbrook, provides a theoretical foundation for understanding how perceived value influences customer loyalty. Holbrook defines consumer value as the subjective evaluation consumers make based on the benefits they receive compared to the costs they incur. He categorizes consumer value into various dimensions, including functional value (related to the quality and performance of a product), emotional value (linked to personal experiences and feelings), and social value (how others perceive the products consumers use). This theory is pivotal in explaining the relationship between perceived value and loyalty, suggesting that when consumers perceive superior value, they are more likely to remain loyal (Holbrook, 1999).

Empirical studies within the airline industry support the critical role of perceived value in fostering customer loyalty. For instance, research on Citilink passengers reveals that perceived value not only directly impacts customer satisfaction but also significantly influences loyalty (Suweri & Hidayat, 2024). Similarly, in the Turkish aviation industry, perceived value, along with brand identification, mediates the relationship between service quality and loyalty, reinforcing that higher perceived value leads to greater customer loyalty (Gurler, 2024). Moreover, during the COVID-19 pandemic, perceived value, particularly in terms of safety measures, played a crucial role in maintaining brand loyalty for airlines (Kim & Kim, 2023).

Based on Holbrook's (1999) theory and these empirical findings, the hypothesis *H1a: Perceived value positively and significantly affects passenger loyalty*.

Perceived value's influence on electronic word of mouth (eWOM) can be understood through the lens of Social Exchange Theory (Blau, 2017), which posits that social interactions are driven by the exchange of resources, where individuals seek to maximize benefits and minimize costs. In the context of eWOM, when consumers perceive high value from airline services, they feel a sense of obligation to reciprocate by sharing positive feedback online, as a form of social exchange. This theory explains why customers who perceive greater value are more inclined to engage in positive eWOM, seeing it as a way to give back to the community or the brand.

Empirical research supports this theoretical perspective. For instance, studies show that perceived value, encompassing elements such as service quality at airports (Nugroho, 2023), brand value (Odabaşoğlu et al., 2022), and informative social media marketing (Jong-un et al., 2023), positively correlates with eWOM behavior. Furthermore, eWOM is particularly impactful on young consumers, with factors like the credibility and quality of the message further driving purchase decisions (Song et al., 2021). However, the relationship is complex, as shown by research indicating that utilitarian value may influence social media behaviors like hashtag use but does not necessarily lead to brand loyalty through eWOM (Kim & Hyun, 2019). Nonetheless, eWOM itself, shaped by perceived value, has a direct impact on purchase intentions for airline tickets (Oktafia & Sutarwati, 2023). Based on this, the hypothesis is proposed *H1b*: *Perceived value positively and significantly affects electronic word of mouth*.

Perceived value plays a pivotal role in shaping the airline brand image, both theoretically and empirically. Social Exchange Theory (Blau, 2017) suggests that consumers evaluate the benefits they receive relative to the costs incurred. In the context of airlines, when passengers perceive high value—whether through service quality, competitive pricing, or enhanced services—they are more likely to develop a favorable impression of the brand. This positive perception contributes to a stronger airline brand image, as customers feel their expectations have been exceeded, leading to more favorable brand associations.

Empirical studies further support this relationship. Research on Taiwanese passengers reveals that perceived value has a significant positive effect on brand image, particularly for both full-service and low-cost airlines (Fu, 2023). Similarly, Choi found that core service quality directly influences perceived value, which in turn enhances the airline's brand image, demonstrating the importance of perceived value as a mediator between service quality and brand perception (Choi, 2023). Furthermore, marketing activities, such as those conducted via social media, can boost perceived value, which further contributes to an improved brand image (Jang & Lim, 2022)

Based on both theoretical insights and empirical findings, the hypothesis *H1c*: *Perceived value positively and significantly affects airline brand image*.

Electronic word of mouth

Electronic word of mouth (eWOM) has a significant and positive influence on passenger loyalty, grounded in both theoretical and empirical evidence. According to Social Exchange Theory, individuals engage in exchanges where they seek to maximize benefits and minimize costs (Blau, 2017). In the context of eWOM, passengers perceive value in the shared experiences and opinions of others, leading to increased trust and favorable attitudes toward the airline. This process enhances loyalty as passengers who trust positive eWOM are more likely to remain loyal to the airline.

Empirical studies provide strong support for this theoretical foundation. For instance, research on Sriwijaya Air passengers in Indonesia shows that eWOM positively affects brand image, which in turn strengthens customer loyalty (Jaman & Sopiah, 2019). Similarly, a study in the Indian airline sector highlights that eWOM, promoted through social media marketing activities, directly contributes to brand loyalty by enhancing brand perception and customer engagement (Khan et al., 2024). Furthermore, the credibility and quality of eWOM messages increase passengers' trust in the airline, reinforcing their decision to stay loyal (Ahmad et al., 2022).

Based on both theoretical insights and empirical evidence, the hypothesis *H2*: *Electronic word of mouth positively and significantly affects passenger loyalty*.

Airline brand image

Airline brand equity strongly influences loyalty, with brand loyalty serving as the key determinant of brand equity in the airline industry (Chen & Tseng, 2010). The brand image, which represents the overall impression passengers hold about an airline, plays a crucial role in determining their loyalty. A strong and positive brand image signals reliability, quality, and value, leading passengers to form stronger emotional and psychological connections with the airline. According to Social Identity Theory (Tajfel & Turner, 1979) individuals tend to identify with brands that reflect their values and identity, making them more likely to remain loyal to such brands.

A strong brand image can significantly bolster customer trust and loyalty, essential for fostering positive eWOM. Research supports this link: brand image directly enhances trust, which then positively impacts eWOM in social commerce (Bui & Chang, 2022). Likewise, brand loyalty—closely associated with brand image—strongly influences eWOM in the airline industry (Samosir et al., 2023). Thus, *H3a: Airline brand image positively and significantly affects eWOM*

Empirical evidence supports this relationship. A study on Taiwanese passengers demonstrated that brand image significantly enhances passenger loyalty, as passengers who perceive the brand positively are more likely to stay loyal to both full-service and low-cost airlines (Fu, 2023). Additionally, research on Royal Air Maroc shows that a favorable airline image boosts perceived service quality and passenger satisfaction, leading to increased loyalty and positive word-of-mouth (Boubker & Naoui, 2022). Similarly, a study on Citilink Indonesia found that both brand image and brand trust are critical drivers of customer loyalty, as they reinforce passengers' confidence in the airline's ability to meet their needs (Aristana et al., 2022).

Thus, a strong brand image cultivates trust and emotional attachment, leading passengers to choose the same airline repeatedly, even when alternatives are available. *H3b: Airline brand image positively and significantly affects passenger loyalty*.

In the context of eWOM, a strong airline brand image amplifies perceived value by reinforcing the credibility and reliability of online reviews and recommendations. Expectation-confirmation theory further supports this, proposing that passengers are more likely to develop loyalty when eWOM aligns with their pre-existing beliefs and expectations about a brand (Oliver, 1980). A strong brand image thus magnifies the influence of positive eWOM by reinforcing these expectations and increasing satisfaction, which strengthens the consumer's trust and connection with the airline (Mathilda et al., 2022).

Moreover, according to brand equity theory, a robust brand image acts as a valuable intangible asset that enhances perceived service quality, customer satisfaction, and perceived value—key drivers of passenger loyalty (Aaker, 2009). Empirical studies show that brand image not only increases customer satisfaction but also boosts the impact of eWOM on loyalty by aligning passengers' expectations with the brand's promises (Yodpram & Intalar, 2020). When a strong airline brand image complements positive eWOM, it acts as a reinforcing factor, motivating customers to form loyalty by validating the positive experiences shared by others. It enhancing the influence of eWOM on loyalty through strengthened trust, perceived value, and expectation alignment (Wijaya & Anjasari, 2022). Building on these theoretical foundations, we propose: *H4: Airline brand image will positively moderate the relationship between eWOM and passenger loyalty*.

2. Method

Data Collection

This study explores the drivers of passenger loyalty within Vietnam's low-cost airline sector, utilizing a structured survey approach. An 18-item questionnaire spanning four core factors—Perceived Value, Electronic Word of Mouth, Airline Brand Image, and Passenger Loyalty—was meticulously crafted, grounded in validated scales and fine-tuned for Vietnam with expert insights. The survey questions were refined with input from aviation, tourism, and consumer behavior experts. Professors, senior lecturers, and experienced researchers from the Vietnam Aviation Academy provided critical feedback, ensuring contextual and cultural relevance for Vietnam's aviation market. Industry professionals with expertise in ground services, airline management, airport administration, and operational services further enhanced the questionnaire's precision. Their practical insights aligned the survey with industry standards and the unique needs of Vietnam's aviation sector. A pilot test involving 22 participants refined clarity, minimizing measurement bias. The final survey, conducted from February to August 2024 via Google Forms, gathered 236 valid responses from a targeted sample of 250 passengers who had flown low-cost airlines. To facilitate convenient participation, on-site surveys were conducted at Tan Son Nhat International Airport and Noi Bai International Airport. Passengers accessed the survey via a pre-designed questionnaire hosted on the Google Forms platform. A clearly displayed QR code was provided at the survey site, allowing passengers to easily scan it with their smartphones, instantly redirecting them to the Google Forms survey. This approach ensured fast, seamless, and user-friendly participation, maximizing the response rate and enhancing the quality of data collection. Hair et al. require a minimum sample size that is 10 times the number of observed variables (Hair et al., 2014), this study's 18 observed variables necessitate at least 180 samples. To enhance data reliability, accuracy, and generalizability, 250 samples were initially targeted, yielding 236 valid responses for analysis.

The passengers who participated in this survey had diverse flight experiences. Most of them had flown with low-cost airlines multiple times, with flight frequencies ranging from occasional travelers (1-2 times per year) to frequent flyers (more than 5 times per year). Their experiences included domestic and international flights, providing a comprehensive perspective on customer satisfaction and loyalty. Table 1 presents the demographic profile of the respondents.

Table 1. Demographic profile of the respondents

Demographic Variable	Number of Respondents	Percentage %
Gender		
Male	112	47,46
Female	124	52,54
Age		
Under 20	6	2,54
21-35	86	36,44
36-50	110	46,61
51-65	26	11,02
Over 65	8	3,39
Education		
Junior high school	5	2,12
Senior high school/vocational	38	16,10
College/University	130	55,08
Postgraduate	63	26,69
Marriage Status		
Single	86	36,44
Married	150	63,56
Monthly Income (USD)		
Less than 300 USD	62	26,27
300 USD - less than 600 USD	102	43,22
600 USD – less than 800 USD	60	25,42
More than 800 USD	12	5,08

Data Analysis and Measurement Approach

Using SmartPLS 4, Structural Equation Modeling (SEM) confirmed reliability and validity, with composite reliability and Cronbach's Alpha (>0.7) assessing reliability, and Average Variance Extracted (AVE) (>0.5) ensuring construct validity. Responses were rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) to capture the nuanced drivers of loyalty within the low-cost airline context.

Measurement Items

Drawing on validated scales, the study adapted measurement items to fit Vietnam's low-cost airline market. Perceived Value (PV1-PV5) adapted from Fu (2023), including "This flight experience provides me with comfort and satisfaction", "I believe this airline has strong potential to grow sustainably in the aviation industry", "Considering the ticket price, I am satisfied with the quality of in-flight services", "The airfare I paid is reasonable for a low-cost airline" and "By purchasing this ticket, I saved significantly on travel costs". Electronic Word of Mouth (eWOM1-eWOM4) items from Kudeshia & Kumar (2017): "I often read reviews and posts from other passengers or friends to ensure I choose the right low-cost airline", "I often read reviews and posts from other passengers or friends to learn which airlines leave a good impression", "I often read reviews and posts from other passengers or friends to gather information about low-cost airlines", "I often read reviews and posts from other passengers or friends to feel more confident in my choice of airline. Airline Brand Image (ABI1-ABI5) based on Chen & Tseng (2010): "The airline is recognized as a leader in the low-cost carrier market in Vietnam", "Using this airline signifies practicality and cost-consciousness", "The airline has a reputation for providing affordable and reliable services", "The airline is recommended by influential figures or local celebrities, aligning with the preferences of Vietnamese consumers", "The airline is known for its consistent on-time performance". Finally, Passenger Loyalty (PL1-PL4) adapted from Chen & Tseng (2010): "I would consider flying with this low-cost airline again in the future, as it offers great value for money", "I would recommend this low-cost airline to others who are looking for affordable and reliable travel options", "I consider myself to be loyal to this airline, as it consistently meets my expectations for budget-friendly flights", "Even if another airline offers similar services, I would still prefer to fly with this low-cost carrier due to its affordability and convenience".

3. Results and Discussion

Measurement Model Assessment

After removing ABI5 due to a low outer loading (<0.4), the analysis in Table 2 confirms that the data satisfies the consistency requirements for the proposed model. Factor loadings exceed 0.4, while Cronbach's alpha (CA) values are above 0.6, and composite reliability (CR) surpasses 0.7 (Peterson & Kim, 2013), indicating robust construct reliability. Additionally, all constructs show Average Variance Extracted (AVE) values over 0.5 (Hair et al., 2014), ensuring that the constructs capture meaningful variance from their measures rather than error, thereby validating their accuracy.

In summary, high factor loadings, Cronbach's alpha, composite reliability, and AVE values collectively establish strong reliability and validity, confirming that the measurement scales accurately capture the intended constructs and solidifying the foundation for further analysis.

This study used the Heterotrait-Monotrait (HTMT) index to assess discriminant validity, ensuring each construct is uniquely measured. HTMT values below 0.9 indicate strong discriminant validity (Henseler et al., 2015). Impressively, all HTMT values in this study fell under this threshold (Table 3), confirming that each construct is distinct. This result demonstrates that our measures effectively capture the unique dimensions of each construct, enhancing the model's overall validity.

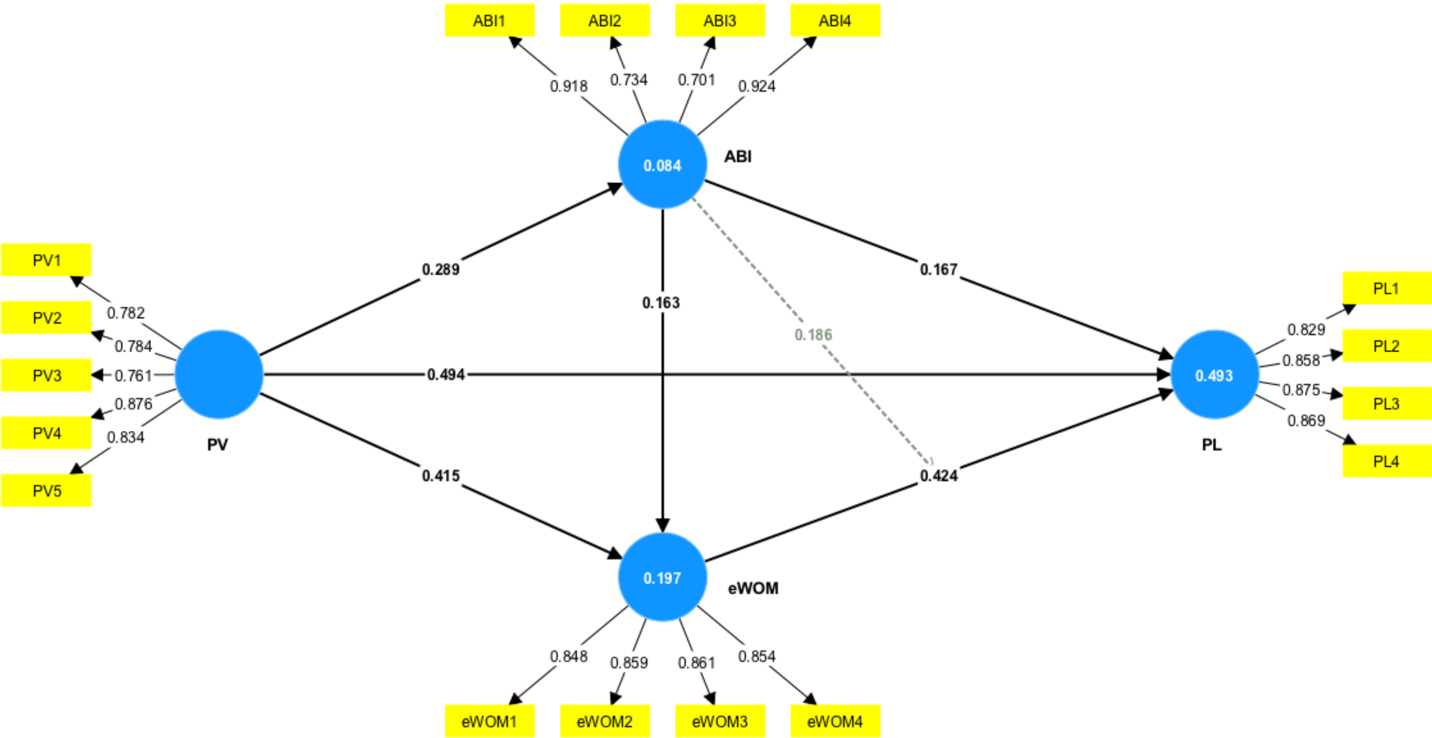

Fig. 1. Research model

Table 2. Construct measurement

Code	Outer loading					CA	CR	AVE
	ABI	PL	PV	eWOM	ABI x eWOM			
ABEI1	0.913							
ABEI2	0.741					0.842	0.888	0.682
ABEI3	0.704							
ABEI4	0.921							
PL1		0.829						
PL2		0.858				0.881	0.918	0.736
PL3		0.875						
PL4		0.869						
PV1			0.782					
PV2			0.785					
PV3			0.761			0.867	0.875	0.654
PV4			0.876					
PV5			0.834					
eWOM1				0.847				
eWOM2				0.861		0.878	0.881	0.732
eWOM3				0.859				
eWOM4				0.855				
ABI x eWOM					1.000			

Table 3. Construct measurement

	ABI	PL	PV	eWOM	ABI x eWOM
ABI	-				
PL	0.324	-			
PV	0.322	0.592	-		
eWOM	0.302	0.691	0.472	-	
ABI x eWOM	0.111	0.329	0.156	0.232	-

Table 4. Explanation of variance and model fit

Variable	R^2	R^2 Adjusted	Q^2
ABI	0.083	0.079	0.051
PL	0.493	0.484	0.351
eWOM	0.173	0.169	0.119
Model Fit	SRMR 0.067	d_ULS 0.688	d_G 0.271

The model's R^2 values highlight its moderate explanatory power, with Passenger Loyalty (PL) achieving an R^2 of 0.493 (adjusted 0.484), meaning that 49.3% of PL variance is accounted for by the model's predictors, along with a strong Q^2 of 0.351, demonstrating robust predictive relevance. Electronic Word of Mouth (eWOM) has an R^2 of 0.173 and Q^2 of 0.119, indicating moderate explanatory and predictive power, while Airline Brand Image (ABI) reflects an R^2 of 0.083 and Q^2 of 0.051, showing a modest level of influence (Hair et al., 2017).

In PLS-SEM, Henseler et al introduced the SRMR (Standardized Root Mean Square Residuals) index to evaluate model fit, suggesting that an SRMR < 0.082 indicates suitability. Other metrics, such as d_ULS < 95% and d_G < 95%, must also meet this standard (Henseler et al., 2016). Model fit indicators—SRMR (0.067), d_ULS (0.688), and d_G (0.271)—confirm the model's suitability, underscoring its effectiveness in capturing the constructs within the low-cost airline sector.

Structural Model Assessment Results

The structural model analysis confirms statistically significant mediation paths, with p-values well within the accepted threshold ($p < 0.05$) (Hair et al., 2017).

Table 5. Assessment of structural model

Mediation Paths	Original sample	P Values	Conclusion
ABI → PL	0.167	0.008	Accepted
ABI → eWOM	0.163	0.013	Accepted
PV → ABI	0.289	0.000	Accepted
PV → PL	0.494	0.000	Accepted
PV → eWOM	0.415	0.000	Accepted
ABI*eWOM → PL	0.186	0.005	Accepted

Specifically, Airline Brand Image (ABI) exerts a notable positive effect on Passenger Loyalty (PL) ($\beta = 0.167$, $p = 0.008$) and Electronic Word of Mouth (eWOM) ($\beta = 0.163$, $p = 0.013$). Perceived Value (PV) demonstrates an even stronger influence across multiple paths: on ABI ($\beta = 0.289$, $p < 0.001$), PL ($\beta = 0.494$, $p < 0.001$), and eWOM ($\beta = 0.415$, $p < 0.001$). These statistically significant relationships highlight the critical role of perceived value in shaping both loyalty and eWOM behaviors, underscoring its central position in the model.

Moderating effect of Airline brand image

The analysis reveals a statistically significant moderating effect of Airline Brand Image (ABI) on the relationship between Electronic Word of Mouth (eWOM) and Passenger Loyalty (PL), with an original sample value of 0.186 and a p-value of 0.005. This finding confirms that ABI strengthens the impact of eWOM on PL, highlighting the critical role of brand image in enhancing loyalty within the low-cost airline context.

The interaction plot illustrates the moderating role of Airline Brand Image (ABI) in the relationship between Electronic Word of Mouth (eWOM) and Passenger Loyalty (PL). As shown, when ABI is high (+1 SD), the positive impact of eWOM on PL is stronger, indicating that a strong brand image amplifies the influence of eWOM on loyalty. Conversely, with low ABI (-1 SD), the impact of eWOM on PL is weaker. This reinforces the importance of brand image in leveraging eWOM to enhance passenger loyalty in the low-cost airline sector.

Discussion of Research Findings

The structural model analysis underscores the pivotal roles of perceived value, brand image, and electronic word of mouth (eWOM) in shaping passenger loyalty within the Vietnamese low-cost airline sector, aligning closely with findings in prior studies. Perceived value plays a central role, significantly enhancing brand image, loyalty, and eWOM behaviors. This result aligns with Holbrook's Consumer Value Theory (1999), which posits that higher perceived value leads to stronger customer loyalty. Social Exchange Theory (Blau, 2017) further supports this, suggesting that satisfied passengers, when perceiving high value, feel inclined to reciprocate through positive eWOM. Similar conclusions are drawn by Suweri & Hidayat (2024) and Gurler (2024) in their respective studies on Citilink and Turkish airlines, where perceived value directly strengthened both loyalty and eWOM. This comprehensive evidence highlights perceived value as a critical component in influencing passenger behavior.

Our findings affirm that perceived value also plays an essential role in boosting brand image, particularly within the low-cost airline context, aligning with Fu's (2023) research on Taiwanese airlines, which demonstrated that perceived value significantly reinforced a positive airline brand image. Choi (2023) also found that high service quality directly impacts perceived value, which subsequently enhances brand image.

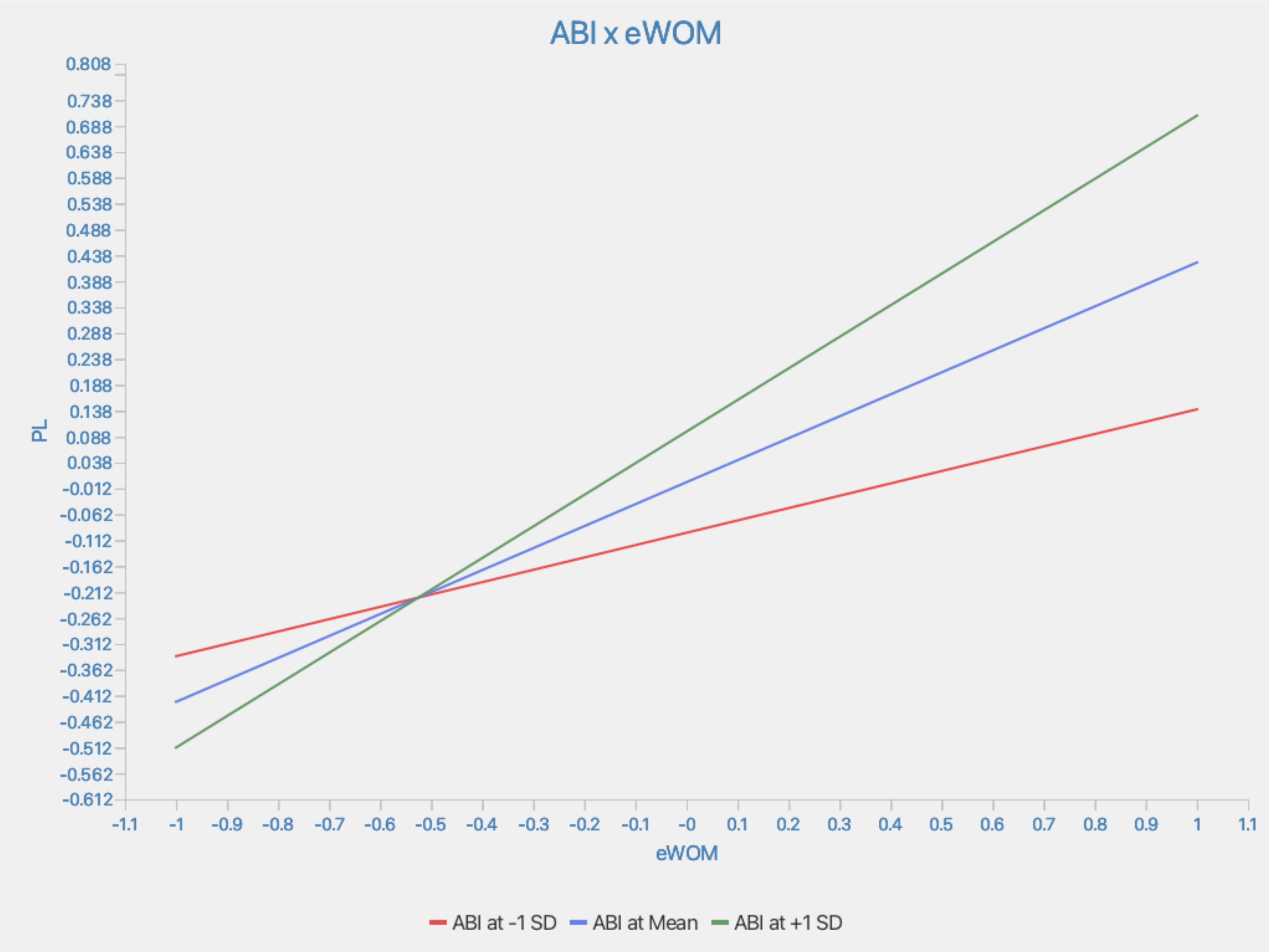

Fig. 2. Moderating effect of airline brand image

Together, these findings underscore perceived value as a key factor for improving brand perception, establishing a favorable image for low-cost airlines.

The analysis further reveals a significant impact of eWOM on passenger loyalty, consistent with Jaman & Sopiah's (2019) study on Sriwijaya Air and Khan et al.'s (2024) findings in the Indian airline industry. These studies demonstrate that eWOM positively shapes loyalty by strengthening brand perception and engaging customers. In this way, eWOM serves as a trusted source of information, fostering a positive image that ultimately drives loyalty.

Airline brand image also profoundly affects loyalty, a conclusion supported by studies on Royal Air Maroc and Citilink Indonesia. Boubker & Naoui (2022) and Aristana et al. (2022) respectively found that a strong brand image fosters trust and emotional attachment, prompting passengers to choose the same airline repeatedly. A well-regarded brand image is associated with reliability and quality, fostering deeper passenger commitment. Our results align with these findings, highlighting brand image as a powerful factor in reinforcing both loyalty and eWOM.

Notably, our model reveals that airline brand image (ABI) plays a moderating role, amplifying the impact of eWOM on loyalty—a finding consistent with Wijaya & Anjasari (2022), who demonstrated that brand image enhances the influence of positive eWOM on loyalty by validating passenger expectations and reinforcing positive experiences. This moderating effect of ABI implies that a strong airline brand image not only supports customer loyalty directly but also enhances the persuasive power of eWOM by lending credibility to the positive reviews shared by others. Therefore, ABI acts as a reinforcing factor, where a well-established brand image validates customer expectations and deepens the impact of eWOM, further strengthening loyalty among passengers.

Managerial Implications

Enhancing Perceived Value to Drive Loyalty and Brand Image: To strengthen passenger loyalty, Vietnam's low-cost airlines should prioritize perceived value by optimizing cost-benefit balance in their services. Strategies could include transparent pricing, value-based incentives (such as special discounts or loyalty points for frequent travelers), and affordable add-ons like flexible baggage options. Ensuring consistent service quality and aligning offerings with passenger expectations will improve perceived value, subsequently enhancing brand loyalty and reinforcing a positive brand image.

Leveraging eWOM as a Strategic Tool for Engagement: eWOM is a critical driver of loyalty in the low-cost airline market, and its role can be harnessed through active engagement with passenger feedback on social media platforms, travel forums, and review sites. Airlines should encourage satisfied customers to share their experiences and can incentivize such actions by offering rewards for reviews or social media shares. Additionally, customer service teams should actively monitor and respond to eWOM, as engaging with feedback (both positive and critical) shows responsiveness, builds trust, and can attract new customers.

Building and Reinforcing a Strong Airline Brand Image: A robust brand image strengthens passenger loyalty and amplifies the influence of eWOM. To foster this image, low-cost airlines should focus on promoting reliability, safety, and consistency in their communications and service delivery. Investments in brand-building activities—such as advertising, partnerships, or Corporate Social Responsibility (CSR) initiatives that align with passenger values—will solidify the brand's reputation. By maintaining this brand image, airlines can position themselves as trusted, high-value options within the competitive market.

Optimizing the Moderating Role of Brand Image in eWOM Influence: Given that a strong brand image enhances the effect of eWOM on loyalty, low-cost airlines should consider campaigns that highlight customer testimonials and positive stories, reinforcing the brand's credibility. Regularly sharing authentic customer experiences across digital platforms can validate expectations, deepen customer trust, and motivate loyalty. This strategy is particularly effective in a low-cost market where trust and perceived value significantly impact purchase decisions.

4. Conclusion

Theoretical Insights

This study contributes significantly to understanding the interconnected roles of perceived value, brand image, and eWOM in shaping passenger loyalty within the low-cost airline industry. Grounded in Holbrook's Consumer Value Theory and Social Exchange Theory, our findings underscore that perceived value is not only a direct determinant of loyalty but also a catalyst for brand image enhancement and positive eWOM. Additionally, the moderating effect of brand image amplifies eWOM's impact on loyalty, suggesting that a well-established brand image validates passenger expectations and strengthens their connection to the airline. These dynamic reveals brand image as a vital reinforcing factor, extending theories of consumer loyalty into the specific context of low-cost airlines.

Practical Implications

For practitioners, this research illuminates strategic priorities for Vietnam's low-cost airlines. By focusing on enhancing perceived value through service quality, value-based pricing, and CSR initiatives, airlines can boost both loyalty and positive eWOM. Moreover, a strong brand image proves essential not only as a direct influence on loyalty but also as a factor that intensifies eWOM's impact, underscoring the importance of consistent branding efforts, customer engagement, and brand-building activities. Together, these insights provide a comprehensive roadmap for airlines aiming to secure a competitive advantage in a rapidly evolving market.

Limitations and Future Research Directions

While this study offers valuable insights into passenger loyalty within the low-cost airline sector, two limitations should be noted. First, the sample is limited to passengers in Vietnam, which may restrict the generalizability of the findings to other markets with different cultural or economic contexts. Future studies could expand on this by including a more diverse sample across various regions to enhance external validity. Second, the study primarily focuses on perceived value, brand image, and eWOM, potentially overlooking other significant factors, such as service personalization or environmental sustainability, which are becoming increasingly relevant to consumers. Future research could investigate these additional variables to provide a more comprehensive understanding of passenger loyalty dynamics in the airline industry.

CRediT Author Statement

Nguyen Anh-Loi: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original. **Ao Thu-Hoai:** Draft Review & Editing, Supervision.

Nomenclature

ABI : Airline Brand Image

AVE : Average Variance Extracted

CA : Cronbach's alpha

CR : Composite reliability

eWOM : Electronic Word of Mouth

HTMTH : Heterotrait-Monotrait

PL : Passenger Loyalty

PV : Perceived Value

SEM : Structural Equation Modeling

SRMR : Standardized Root Mean Square Residuals

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Research Article

Design and Realization of an Electronic Pitot Cover That Will Not Be Forgotten Before the Take-Off

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Abstract

In this study, an electronic cover system was designed and produced that will prevent forgetting before take-off at aircraft. Proposed system, which has a very simple but effective structure, basically consists of microcontrollers, wireless communication modules, and switches. This prototype system has two components, the pitot component and the cockpit component. If the pitot component is attached to the pitot tube, the system starts working when the cockpit component is active. In the designed system, both components communicate with each other wirelessly. As a result of this communication, both components flash the powerful light-emitting diodes (LEDs) on them at certain intervals (by making a flash effect). When the power LEDs are blinking, it means that the cover is attached to the pitot tube. In this way, both the marshalling officers and the pilot are warned that the cover is attached to the pitot tube, preventing a possible accident.

Keywords

Pitot Tube
Cover
Take-Off
Crash
Pilot Warning System

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1. Introduction

As is known, the first people to fly an airplane with a motor for the first time in history were Orville Wright and Wilbur Wright, known as the Wright brothers. In the first plane that the Wright brothers flew, only three instruments were used to ensure a safe flight. These were the engine tachometer, anemometer, and stopwatch. However, many complex and sensitive instruments and indicators are used in today's aircraft. Altitude, airspeed, vertical speed, magnetic direction, artificial horizon, fuel amount, fuel pressure, oil amount, oil pressure, temperature, turn coordinator, and navigation indicators are just a few of them. Among these indicators, total and static pressures must be measured for the altitude, air velocity, and vertical velocity indicators to work.

Normal atmospheric pressure, which acts equally on the entire surface of an aircraft, regardless of whether it is moving or immobile, is called static pressure. However, when the aircraft is in motion, the leading edges are subjected to additional pressure to the static pressure. This pressure is defined as dynamic pressure. So, a pressure called the Pitot pressure, which is the sum of the static and dynamic pressure, acts on the leading edges of the aircraft. Pitot-static systems are used to measure these pressures, the internal structure of which is shown in Fig. 1.

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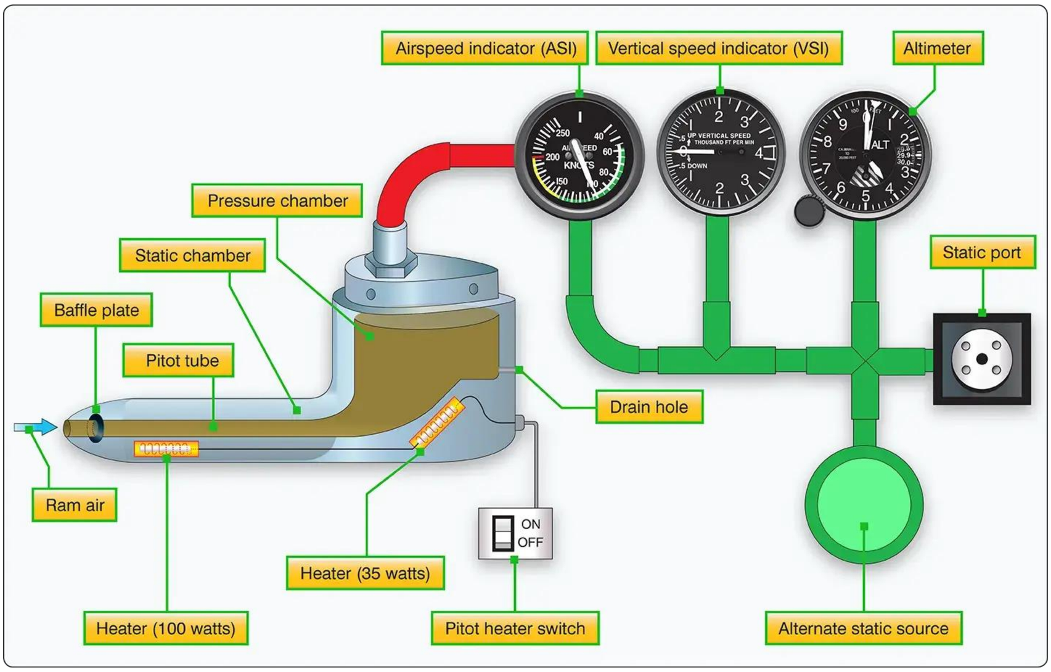


Fig. 1. A typical pitot-static system and the indicators it feeds (Anonymous, 2023).

Fig. 2. Examples of pitot cover.

As demonstrated in Fig. 1, the pitot tube used to measure the total pressure has an open end facing the flight direction of the aircraft. This hole, which has a very small diameter, must always remain open during the flight. Any blockage here will cause the aforementioned altitude, airspeed, and vertical velocity indicators to show incorrect values. If one of the dynamic or static ports is clogged, the Pitot tubes can overestimate the velocity by up to about 5.6% (Golparvar and Yapici, 2020). In order not to experience such a danger during the flight, there are drain holes and heaters in the pitot tube as demonstrated in Fig. 1.

However, clogging of the Pitot tube can also occur when the aircraft is parked. Because dust or sand particles carried by a strong wind can block this hole even when the plane is parked. In addition, since the Pitot tube is warmer at night compared to other environments, it can also be used as a nest by small-sized creatures. Therefore, when the aircraft is parked, the protruding probe of the pitot tube should be covered with appropriate covers. There are pitot covers produced in different ways from many different materials. Fig. 2 shows various pitot covers. In order to prevent these covers from being forgotten during the pre-flight checks, a very striking streamer, flag, or strip, approximately half a meter long, is attached to them. The streamer is also seen in Fig. 2.

In the pre-flight checks of the pitot/static system, the following factors are considered (CAE, 2014):

- All covers have to be removed and stacked.
- All tubes and holes have to be cleaned.
- The Pitot heater has to be running.

Because of the stress and overwork of the relevant personnel and the pilot, forgetting the cover is attached to the Pitot tube or using this place as a nest by small-sized creatures causes disruption of the voyage and even an accident.

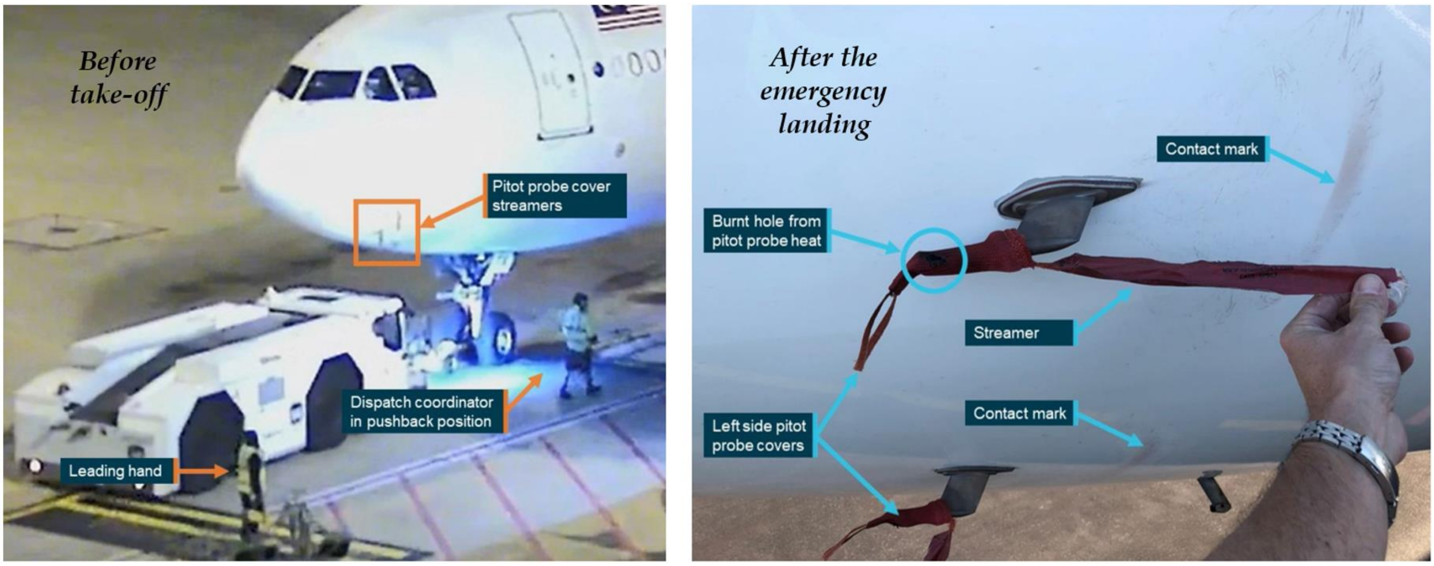


Fig. 3. Images of the Malaysia Airlines plane before and after it took off on 18 July 2018 with the Pitot cover hung up forgotten (ATSB, 2022a).

For example, on 18 July 2018, an Airbus A330 aircraft belonging to Malaysia Airlines took off from Brisbane to Kuala Lumpur with all three Pitot covers hung up. When it was understood that the indicators were showing incorrectly, an emergency landing was made at the same airport by taking all risks. This status is shared in full detail in the report published by the Australian Transport Safety Bureau (ATSB) and given in (ATSB, 2022a). Fig. 3 (the view before take-off) shows that the three Pitot covers are still attached while the A330 is being pushed back. The damage caused to the airframe during the flight by the streamers attached to the Pitot covers in this short-term flight, where there was no loss of life, can be easily seen in the image taken immediately after the emergency landing and shared in Fig. 3.

However, Pitot tube obstruction is not always so easily overcome. Flight 301, operated by Birgenair on 6 February 1996, with a Boeing 757-225 aircraft with the tail register TC-GEN, ended with an accident shortly after the aircraft took off from Puerto Plata International Airport. All 176 passengers and 13 crew members on board the plane, which crashed 26 km northeast of Puerto Plata, died in this crash. As a result of the research, it was understood that a small creature nested in one of the Pitot tubes of the aircraft, so the speed indicators showed differently, and the autopilot, which took the clogged Pitot tube as a reference, reduced the speed of the aircraft, so the aircraft was exposed to stalls and crashed (Hall, 1996; Ortiz, 1996).

Despite these events and the precautions taken, it is known that similar events have been repeated in the recent past. For example, on 27 May 2022, an Airbus A350-941 of Singapore Airlines was to be pushed back to operate flight SQ256 from Brisbane Airport. However, minutes before pushing, it was noticed by a staff member whose job was only to refuel, that the Pitot covers were still attached. Thereupon, a licensed aircraft maintenance engineer (LAME), who should have done this work earlier, removed the Pitot covers one minute before departure time (ATSB, 2022b).

When the three examples given are examined, it is possible to experience fatal accidents at any time due to the plane taking off without removing the Pitot cover, or clogging it while parked because the cover is not installed.

2. Literature Review

Academic studies conducted to solve the problem defined above were searched in accessible online databases using the keyword "pitot tube". The studies reached are summarized below.

Klopfenstein Jr (1998) presented a comprehensive guide to measuring air velocity and airflow using a Pitot tube. It was emphasized that the Pitot tube and air passages should be calibrated in a wind tunnel. Calibration was carried out using a standard wind tunnel and measurements were made at different flow rates. A computer-aided data acquisition system was designed, the measurement data were processed and calibration factors were applied. The article aimed to provide practical information on Pitot tube-based measurement techniques for field engineers.

Dobrowolski, Kabaciński, and Pospolita (2005) presented mathematical models of flow measurement devices such as the self-averaging Pitot tube. Such flow meters were distinguished by their advantages of lower pressure losses in large-diameter pipelines, high-temperature tolerance, and easy installation. In the paper, a model was developed that analyzes the influence of the shape of the flow sensor, its structural features, and flow conditions on the differential pressure. The model was validated by calculating the velocity and pressure fields around and inside the sensor using numerical methods. The study explained the relationship between the Reynolds number and the flow coefficient and presented results applicable to metrology.

Sun, Li, and Zheng (2009) investigated the effects of incorrect installation of the Pitot tube on measurement performance. In the study, the impact of installation angles on measurement accuracy were evaluated theoretically and experimentally; correction factors were developed for errors caused by the deflection angle. The findings showed that mistakes can be reduced with correction factors that are symmetrical with horizontal angles and decreasing and increasing with vertical angles. With this method, measurement errors can be reduced to less than 30% even in the case of incorrect installation.

Cho et al. (2012) presented a GPS-based calibration method to improve the accuracy of air data systems used in aircraft. The study developed for the smart unmanned aerial vehicle (UAV), a tilt-rotor unmanned aerial vehicle built by the Korea Aerospace Research Institute, addresses the critical challenges in measuring airspeed, barometric altitude, and sideslip angle. Kalman filters and GPS speed information were used to calibrate the errors in static pressure measurements reflected in the airspeed and altitude calculations resulting from the placement of the pitot-static tube in the fuselage. The proposed methods were validated with simulation and real flight data of the smart UAV.

Imai, Klockowski, and Varela (2013) presented a method based on error signatures to detect and correct sensor errors in spatiotemporal data streams. Error signatures are defined by mathematical models to identify data inconsistencies. The method was tested on a specific Cessna flight and the 2009 Air France AF447 accident. For the Cessna flight, scenarios, where the Pitot tube (airspeed indicator), GPS, and both failed, were simulated. The error detection accuracy was 93%, and the maximum correction time was 5 seconds. The Pitot tube failure for the AF447 accident was analyzed with real flight data. The error was successfully detected and corrected within 5 seconds. The overall accuracy was 96.31%. The developed method increased data accuracy and provided an effective solution for flight safety. In the future, the integration of this approach to larger-scale systems and autonomous aircraft is targeted.

Li et al. (2014) discussed the difficulties encountered in determining and calibrating the discharge coefficient of average Pitot tubes used in large-diameter pipes where fully developed flow cannot be achieved. In particular, the effects of elbows (single elbow, double elbows in the same plane, or different planes) in the upstream flow profile were investigated by numerical simulations and experiments. Using the standard k-ε turbulence model, the velocity profiles after the elbow were evaluated, and positive and negative deviations in the discharge coefficients were observed. By comparing the simulation and experimental results, models were developed to correct these effects in the calibration of flowmeters in large-diameter pipes.

Takahashi and Shimoyama (2018) designed a waterproof Pitot tube to measure air velocity during the flight of seabirds. This tube is waterproof via a nano-porous membrane and can perform high-precision measurements with piezo resistive differential pressure sensors. The manufacturing processes, sensor calibration, and experimental verification studies are detailed. The results show that the device can reliably measure air flow velocity both underwater and in open-air conditions. This innovative design contributes to airflow measurement applications in harsh environmental conditions.

Hagiwara et al. (2019) presented an underwater Pitot tube developed for measuring the swimming performance of marine animals. In traditional Pitot tubes, water bubbles entering the tube inlet affect the measurement accuracy, while in this new design, the inlets are closed with thin elastic films. In addition, the incompressible liquid inside the tube and a piezo resistive pressure sensor allowed accurate measurement of the water flow rate without being affected by hydrostatic pressure during deep dives. Its compact structure is suitable for use without hindering the natural movements of marine animals. Tests showed that the device responds quickly to air-water transitions and successfully measures water flow at different speeds.

Golparvar and Yapici (2020) developed a three-dimensional model to model and analyze the blockage situations of the Pitot tube. The developed model simulated the blockage situations of both dynamic and static ports. In case of blockage of the dynamic port, the sensor shows values about 5.6% above the actual speed, while blockage of the static port leads to slightly lower speed values. The study aims to contribute to the development of alternative designs to increase the reliability of these sensors and prevent aircraft accidents.

Sun and Gebre-Egziabher (2020) presented a fault detection and isolation algorithm using dual Pitot tubes for the design of reliable air data systems for UAVs. The algorithm works in integration with an accelerometer (IMU), a GNSS receiver and two synthetic air data systems (SADS) and evaluates each Pitot tube independently. It detects and isolates faults with residual thresholding and decision logic based on redundancy analysis. The system also calculates protection levels against faults caused by aircraft dynamics and external factors. Simulation results have shown the effectiveness of the algorithm in developing reliable and low-cost UAV air data systems.

Zhong et al. (2020) developed a method to automatically identify pitot tube caps using a UAV to prevent human-induced maintenance errors such as failure to remove pitot tube caps. In the study conducted on 36 field images, the images were processed with grayscale and color histogram extraction methods, and then errors were identified using support vector machines (SVM). SVM parameters were optimized with the cross-validation (K-CV) method and 96% accuracy was achieved. The method aims to increase the health management capabilities of aircraft pitot-static pressure systems.

Kishimoto et al. (2021a) developed a compact Pitot-static tube-based water flow sensor used for biological data collection (biologging) to study the behavior of marine organisms. Due to its design based on the Pitot tube principle, it can precisely detect water flow velocity by measuring differential pressure. The developed sensor responded to water flow velocity between 0.2 and 1.6 m/s with sufficiently high sensitivity.

Kishimoto et al. (2021b) presented a closed-inlet Pitot-static tube-based water flow sensor designed to study the swimming behavior of marine animals in their natural habitat. The sensor used a structure filled with incompressible liquid and sealed with silicone membranes to detect water flow velocity by differential pressure measurement. This small-sized, lightweight, and pressure-resistant sensor can measure water flow velocity between 0.2 m/s and 1.6 m/s with high precision. This design solved the long-term measurement difficulties of existing sensors and offered a practical innovation in marine biology research.

Tabanlı and Yüceil (2021) discussed the design, analysis, and testing processes of a pitot-static probe to perform speed and altitude measurements of aircraft in the Mach range of 0.5-0.95. The probe, optimized using computational fluid dynamics (CFD) analysis, was tested in the ITU Trisonic wind tunnel and achieved error rates of 0.38%, 0.1%, and 0.07% for static pressure, total pressure, and Mach number measurements respectively. The probe design took into account factors such as nose geometry, pressure port placement, and turbulence effects, and observed the effects of shock waves on measurement accuracy at high speeds. The study presented a probe design capable of making accurate measurements in the subsonic and transonic regimes.

Pechout et al. (2022) used a high-speed pressure difference Pitot tube as an innovative method to measure exhaust flow rate. With a sampling frequency of 5000 per second, this tube captured the high-amplitude exhaust gas fluctuations, especially seen in small engines, and provided accurate and continuous flow data, unlike traditional methods. The Pitot tube was calibrated at different engine speeds and loads, providing high-precision instantaneous exhaust flow data for emission measurements. It was shown its usability for both laboratory and real-world driving conditions in emission analyses.

Ribeiro et al. (2022) presented the design and sensitivity analysis of a calorimetric solid-state thermal mass flow sensor (TMFS) operating in high-speed and high-temperature environments as a solution to the icing problems of existing pitot tubes used in aircraft air data systems. The sensitivity of the sensor was evaluated by increasing the distance between the heater and the thermal sensors and adding a thermal barrier made of Parylene-N material; it was determined that these arrangements increased the temperature change sensitivity by 80%, the speed change sensitivity by 100% and the overall sensitivity by 6 times. Simulations performed with COMSOL Multiphysics and Simulink software confirmed the improvements in the durability and performance of the sensor, and it was concluded that this design was ready for wind tunnel tests as a reliable alternative against icing.

Diniz and Pacheco (2023) investigated the estimation of heat transfer coefficient (HTC) with Steady-State Kalman Filter (SSKF) to detect icing in pitot tubes in real-time. This computationally efficient method determined HTC changes with high accuracy and provided rapid recovery in sudden changes. The approach, which allows real-time monitoring and icing control, aims to increase aircraft safety and prevent accidents. It has the potential for practical use in aircraft systems by providing low-cost and fast solutions.

As can be seen, there is only one study on the detection of the Pitot cover. In the study conducted by Zhong et al. (2020), image processing-based Pitot tube cover detection was attempted. In this context, images of 36 different Pitot tubes with and without a cover were taken and processed, and then the presence of the cover was tried to be determined. However, as a result of this determination, it was not shared whether the pilot was warned before the flight or how this information was transferred to the pilot.

In this study by us, a Pitot tube cover with electronic components was designed. In the design made, whether the Pitot tube cover is forgotten in the Pitot tube will be determined electronically by the designed circuit. If, in the pre-take-off checks, the cover is forgotten attached to the Pitot tube (i.e. cover is not removed), the pilot will be visually alerted by a very high flux light in the cockpit. In this way, possible accidents due to forgetting the cover attached to the Pitot tube will be prevented.

3. Material and Method

In the designed system, it is determined whether the Pitot tube cover is removed or not and the pilot is warned about this situation. Therefore, the system consists of two components. The first of the components is the cover designed to be attached to the Pitot tube and specific to the aircraft. The other is the component placed in the cockpit to warn the pilot if this cover is forgotten attached to the Pitot tube before the flight.

From the moment the designed cover is attached to the Pitot tube, it will wirelessly send information to the component in the cockpit. This information sent will cause a high-intensity light emitted diode (power LED) on the component in the cockpit to light up. The illumination of the Power LED indicates that the cap is attached to the Pitot tube. There is also a power LED on the cover attached to the Pitot tube. The illumination of this LED indicates that the component in the cockpit is energized and communication is provided with it. Therefore, due to these LEDs, it can be easily understood that all system components are active and that the cover is attached to the Pitot tube.

The designed system consists of electronic components and boxes in which these components are placed. For this reason, it would be more accurate to examine the designed system under two headings as electronic design and mechanical design.

3.1 Electronic Design

The basic electronic materials used in the designed system are Arduino Nano, NRF24L01, and NRF adapter.

In the study, two Arduino Nanos were used as microcontrollers both to ensure the compatibility of the receiver and transmitter circuits and to control the operation of the system. Weighing 7 grams, this microcontroller is 45 mm long and 18 mm wide.

In the designed system, a low-cost wireless communication module NRF24L01 was used to provide communication between the component attached to the Pitot tube and the component placed in the cockpit. Since there is mutual communication between the two components, both components work as both receiver and transmitter. This module, which has a power amplifier and a surface-mounted antenna, provides wireless communication 2.4 GHz up to 100 meters in the open area. The operating voltage of NRF24L01 is in the range of 1.9V to 3.6V. An NRF adapter was used both to provide this required voltage and to ensure that the module worked more stably.

Besides these basic electronic components mentioned above, power LEDs, resistors, semiconductor switches, and mechanical switches were also used. In addition, during the trial of the design, 12V-3Ah batteries were used because we did not have any permission to interfere with the electrical system of the aircraft. The schematics of the circuits that are formed using these electronic materials are shown in Fig. 4. Normally, one jack is connected to the batteries in parallel so that they can be charged. However, these jacks are not shown in the circuit diagrams in Fig. 4.

The switch in the component to be attached to the Pitot tube is a wheeled limit switch. This switch was used to automatically ensure that the circuit was powered and started working as it should when this component was attached to the Pitot tube. Therefore, no external switch was used to manually open and close the circuit.

The activation of the component to be placed in the cockpit could also be done automatically via the master switch on the aircraft, without the need for any manual switch. However, since we do not have any permission to interfere with the electrical system of the aircraft, the activation of the cockpit component is carried out using a normal on-off switch. Therefore, the materials and wiring diagrams used in both circuits are almost the same, except for the switches.

In the software of the designed system, a password was used to ensure that only the system components belonging to the same aircraft matched with each other. In this way, it has prevented different aircraft send information to each other and the system works incorrectly.

3.2 Mechanical Design

In order to mount the electronic circuits detailed above to the Pitot tube and the cockpit, two boxes were designed in the program called Solidworks. These designed boxes were produced using a 3D printer.

A solid model image of the cover to be installed to the Pitot tube of the aircraft is shown in Fig. 5. This box, which has 106x160mm dimensions, was designed as a normal Pitot tube cover. In other words, it is capable of preventing dust and small creatures from entering the Pitot tube while it is attached to the aircraft. The cylindrical section highlighted by number 1 in the Pitot component is such that this box is fitted to the Pitot tube of the aircraft to be tested with appropriate tightness. In addition, this section is designed to be suitable for the operation of the wheeled limit switch mentioned above. The chamber shown by 2 is the section where the designed electronic circuit will be placed. The circle numbered 3 in this chamber is for the placement of the power LED. The circle indicated with number 4 is for plugging the jack to be used while charging the battery. The chamber shown with 5 is for the placement of the battery that will supply the relevant circuit. The ring on the bottom surface of the box was created for attaching the streamer with "Remove before flight" written on it.

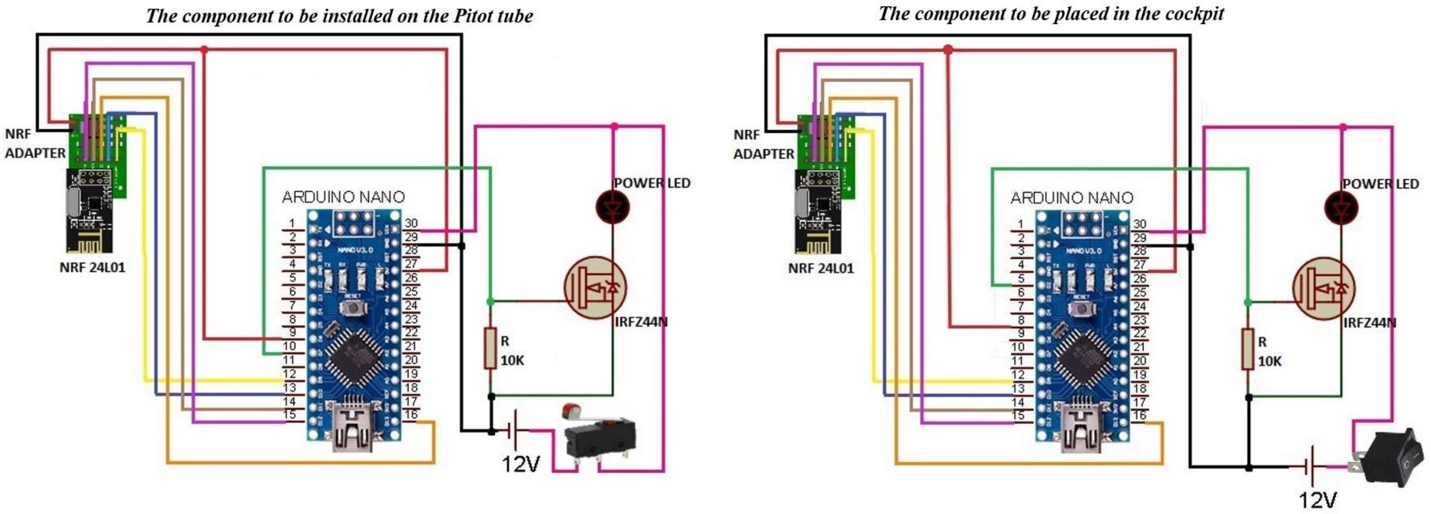
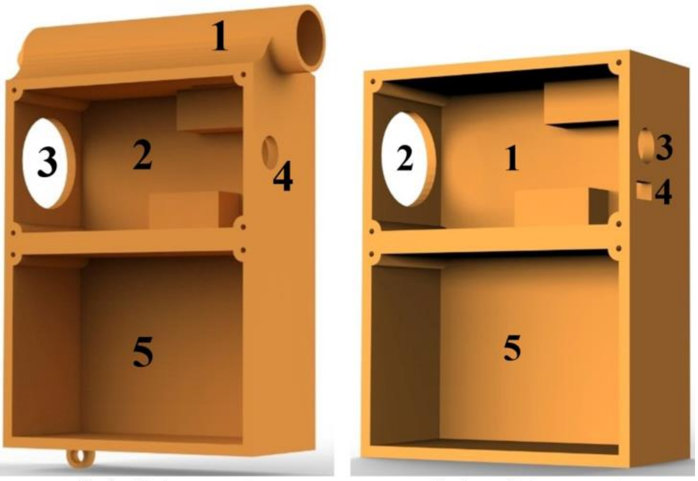


Fig. 4. The circuit diagrams of the designed system



for the Pitot component *for the cockpit component*

Fig. 5. Solid model images of the designed boxes.

A solid model image of the second box with dimensions of 106x136mm, which is designed to contain the circuit to be placed in the cockpit, is also given in Fig. 5. The chamber in the second box, highlighted with 1, is the section where the designed electronic circuit will be placed. The circle indicated by the number 2 in this chamber is for the placement of the power LED. The circle indicated by the number 3 is created for the insertion of the jack to be used during the charging of the battery. Section 4 of this chamber is for the insertion of the on-off switch. The chamber shown with 5 is the battery section designed according to the dimensions of the battery that will feed the circuit.

4. Experimental Studies

The currents drawn by the designed circuits will affect the discharge times of the batteries used. For this reason, the currents drawn by the circuits should be measured before the tests are started. As it will be remembered, the circuits are similar except for the switches used. For this reason, measurements were made in only one of the circuits. In the current measurement made on the cockpit component, it was seen that the current drawn was 41mA when the power LED was not lit (the Pitot component was passive). The current drawn by the cockpit component when the power LED is lit (when the Pitot component is active) is 93.6mA.

The designed system was primarily tested with the components side by side. In the first stage, the switch in the cockpit component was turned to the ON position, and this circuit was fed. This will be understood by the light up of the small red LED, which indicates that the Arduino Nano is powered, in the test images given in Fig. 6. At this stage, since the wheeled limit switch inside the Pitot component is not active, the Pitot component is inactive (the LED on the Arduino Nano is not lit). Therefore, there is no communication between the two components at this stage. The fact that there is no communication can also be understood from the fact that the power LEDs on both circuits do not light up.

When the Pitot component of the implemented system is attached to the Pitot tube of the aircraft, the wheeled limit switch in this component will enable the circuit to be active. This activation was carried out using the finger during the testing process. As demonstrated in the picture in Fig. 7, with the limit switch active, the Arduino Nano in the Pitot tube component was also energized and then began to communicate wirelessly with the cockpit component. It can be understood from the green power LEDs on both components that the communication has taken place. Power LEDs also indicate that the system is working properly and that the designed Pitot component is attached to the Pitot tube.

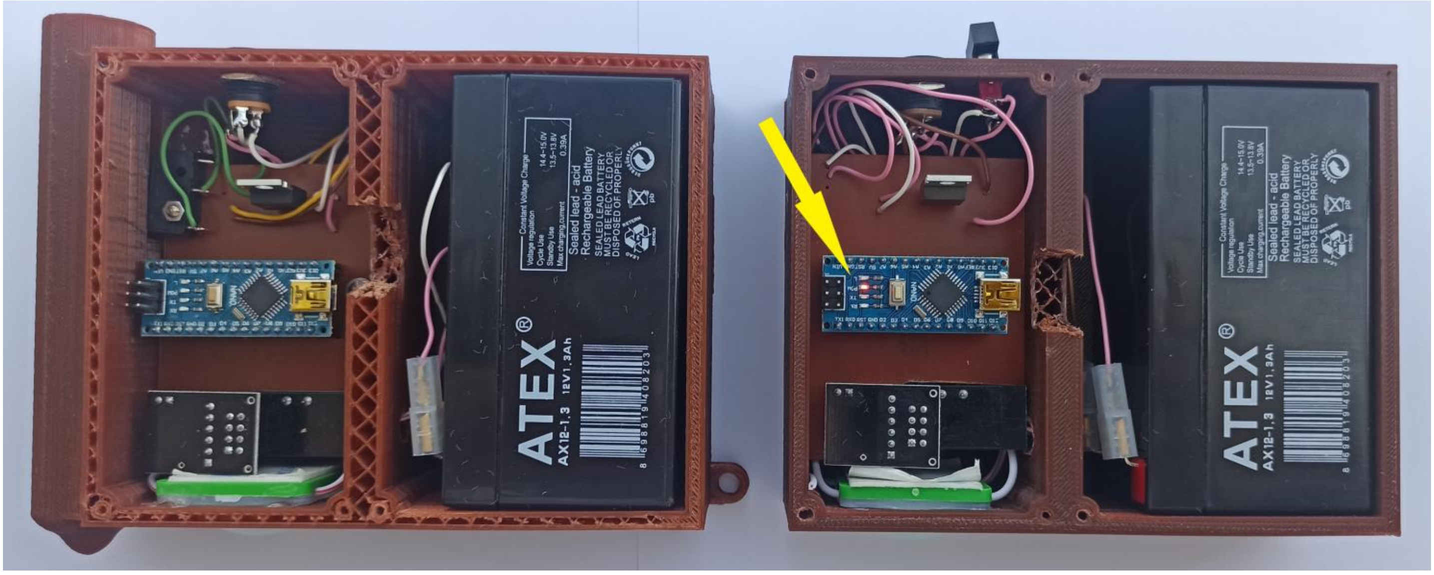


Fig. 6. The case that only the cockpit component is active in the designed system.

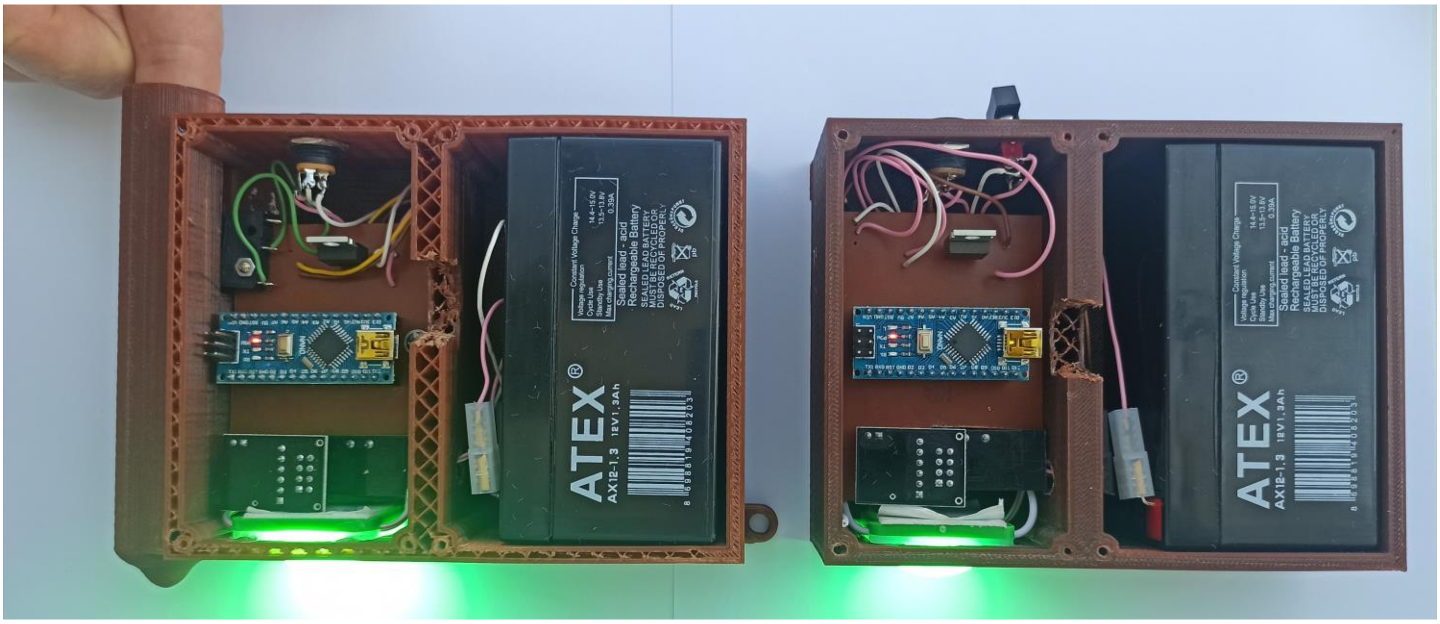


Fig. 7. The case that both components are active in the designed system.

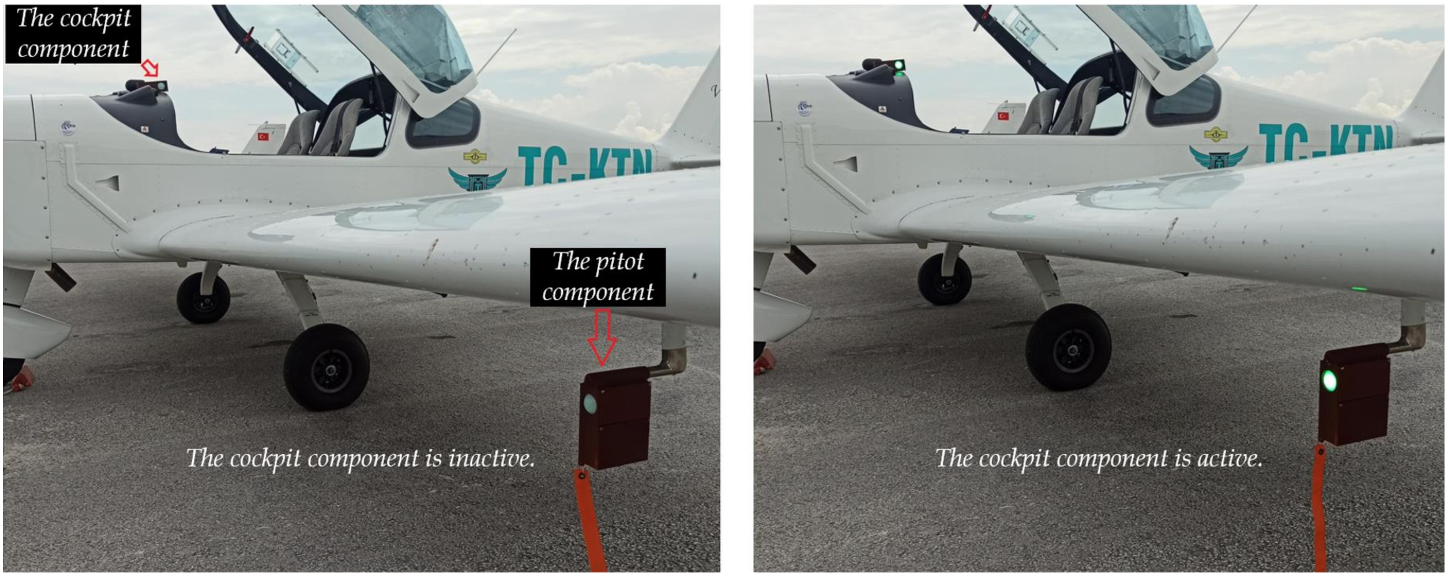


Fig. 8. The cases where the cockpit component is passive and active on the Viper SD4.

Fig. 9. The views of the cockpit component from inside and outside of the cockpit on the Viper SD4 (the switch is at the ON position).

Fig. 10. A picture taken during the operation of the implemented system on the Cessna 172.

After this preliminary test process, the tests on the aircraft were started. The tests were carried out on two different aircraft, the Viper SD4 and the Cessna 172. First of all, information and images of the test on the Viper SD4 will be shared in detail.

In the first part of the test on the aircraft, the cockpit component was not activated, that is, the switch was left in the OFF position. Therefore, no communication took place between the two components. Accordingly, the green power LEDs on the components did not light up. This status is clearly seen in the picture given in Fig. 8.

In the second part of the test, the switch on the cockpit component was turned to the ON position, and the circuit was activated. The active cockpit component has started communicating with the other component attached to the Pitot tube. Accordingly, the green power LEDs on the components started to light up. This status is also clearly seen in the picture given in Fig. 8. The orientation of the cockpit component is turned towards the camera in order to show in the same picture frame that, the power LEDs on both components are lit. But the actual position of this component is with the power LEDs facing the pilot. This status is demonstrated in Fig. 9. It is very unlikely that the pilot would not notice the high-intensity power LED, which indicates that the cover is still plugged into the Pitot tube. This is also clearly seen in the picture in Fig. 9.

Similar tests were performed on Cessna 172, which had the same Pitot tube diameter. In the tests carried out with the same stages, it was observed that the system also worked successfully on the Cessna 172, and the structural differences of the aircraft did not cause a negative effect on the operation of the system. A picture taken during the tests on Cessna 172 and showing that the system is working properly is shared in Fig. 10. In order to be able to show in the same picture frame that, the power LEDs on both components are lit, the direction of the component placed in the cockpit is turned towards the camera.

5. Result and Discussion

In this study, an electronic system was designed and produced as a prototype to prevent the Pitot covers from being forgotten attached to the Pitot tube before flight, which may cause accidents in aircraft. The system consists of a Pitot component attached to the Pitot tube and a cockpit component located within the cockpit. These components communicate wirelessly and when the Pitot component is installed, the LED lights on them flash at regular intervals (flash effect) to warn both the aircraft ground officer and the pilot. In addition, a buzzer system planned to be integrated into the cockpit component will enable the pilot to notice the situation.

The system has two current shortcomings: manual activation and energy source problems. First, the cockpit component is currently activated manually. However, this shortcoming can be easily resolved if the system is accepted by aircraft manufacturers. The cockpit component can be integrated with the master switch that provides control of the main electrical system in the aircraft. Thus, the system will be activated automatically when the pilot turns on the main switch.

The second shortcoming is that the system's components currently operate on their own batteries. This requires regular charging or replacement of the batteries. However, this shortcoming could easily be remedied if the system were adopted by aircraft manufacturers. For example:

- The cockpit component can be integrated directly into the cockpit and powered by the aircraft's electrical system.
- The Pitot component can be powered by the existing power line used for the Pitot tube heaters with minor revisions.

Implementation of the study will require certain processes:

- Availability of Components: System components must be designed for serial production and manufactured with materials that comply with aviation standards.
- Approval Processes: The system must be certified by civil aviation authorities and must be subject to the necessary regulations for use on aircraft.
- Pre-Flight Checks: The system must be included in the aircraft maintenance documentation (preflight check task card) and integrated into control procedures.
- Responsible Personnel: Responsibilities in maintenance and control processes will need to be distributed to technical personnel in the B1 (mechanical) and B2 (electrical/avionics) categories.
- Team Actions and Reporting: A protocol must be established for pilots and ground staff to effectively monitor and report warnings provided by the system.

6. Conclusion

This study focuses on the design and prototype production of an innovative electronic system that aims to increase aircraft safety. The proposed system aims to prevent accidents caused by forgotten Pitot tube covers and offers a wireless solution consisting of two main components. The main contributions of the study are as follows:

- Increased Safety: The system aims to minimize human error by providing visual and auditory warning to pilots and ground personnel.
- Industrial Applicability: The system is designed to be easily integrated with existing aircraft systems if accepted by aircraft manufacturers.

However, the system in its current form has two main limitations:

- Requires manual activation.
- Power continuity issues due to battery usage.

Both problems can be easily solved if aircraft manufacturers support system integration. As the authors, we believe that this study will shed light on future research and applications. In order to increase the applicability of the system on an industrial scale, more comprehensive tests should be conducted and its compliance with international aviation standards should be ensured.

CRediT Author Statement

Cemile Arslan: Software, Investigation, Data Curation, Funding acquisition, Methodology. **Fatih Alpaslan Kazan**: Conceptualization, Validation, Writing – Original Draft & Editing, Visualization, Methodology. **Mustafa Arslan**: Methodology, Validation, Resources, Funding acquisition, Investigation.

Nomenclature

ATSB : Australian Transport Safety Bureau

GPS : Global Positioning System

LAME : Licensed Aircraft Maintenance Engineer

LED : Light-Emitting Diode

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Research Article

A Financial Examination of the Causes of the Boeing Company's Late Aircraft Delivery

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Abstract

Boeing's efforts to develop next-generation aircraft types and present them to customers have been unsuccessful due to delayed deliveries caused by technological and management issues. The evident challenges with the Boeing 737 MAX, the initial postponement of the delivery of the Boeing 787 Dreamliner due to organizational processes in the supply chain, and the current delays in the delivery of the Boeing 767 and Boeing 777 types have impacted the company's financial performance. The study aims to analyze the reasons behind these challenges, identify critical factors influenced by the delivery process, and reveal the financial losses resulting from delayed aircraft deliveries. The study's findings reveal that Boeing faces unpredictable customer issues and intense stakeholder pressure to pay late delivery penalties, leading to significant impacts on the production schedule and financial downturn. Boeing Company, along with a postponed entry schedule to service for early ordered aircraft, has indeed contributed to global delivery issues, resulting in a three-year delay and significant penalties.

Keywords

Boeing Company
Aircraft
Delivery
Delay
Supply Chain Management
Financial Analysis

Time Scale of Article

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1. Introduction

Since its establishment, Boeing has designed, manufactured, implemented, and delivered thousands of commercial aircraft worth hundreds of billions of dollars to customers in more than 150 countries. Through the implementation of new technology programs, the aerospace industry has introduced a novel production system to develop the next generation of aircraft. On the other hand, the aviation industry has a highly globalized market structure, making the role of involved stakeholders increasingly crucial in delivering ordered products to potential customers. As the production of aircraft increases, the manufacturer's influence on the distribution process also increases. Consequently, the management of supply chain strategy is becoming increasingly crucial to prevent delays in delivery and production processes (Mocenco, 2015).

Due to the increasing demand for air transportation and the continuously expanding aviation industry, Boeing has become a leading exporter of commercial aircraft, leveraging a global supplier base to enhance its economic capabilities. Nowadays, the company produces the narrow-body Boeing 737 family and the wide-body Boeing 747, 767, 777, and 787 families of airplanes. Nearly 10,000 next-generation commercial jetliners, including the Boeing 737 MAX, 787-10 Dreamliner, and Boeing 777 X, are currently in service worldwide; however, 5866 aircraft remain undeliverable (Boeing, 2023), Table 1.

In order to meet customer requirements, the supply chain management structure of the Boeing company must offer multi-stage multinational operations to ensure proper delivery of its outstanding orders (Behrens, 2010). Apart from the aviation industry, many companies face challenges due to the pressure to meet

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customer requirements (Miron-Spectar et al., 2011). Consequently, the rapid progress in aircraft manufacturing in recent years has led to high-risk supply chain management, which is vulnerable to the delivery plan (Treuner et al., 2014). Boeing reported operating losses of about 650 million USD in Quarter 4, 2022, contrary to expectations that the aircraft giant would turn a profit. The company attributed the unexpected loss to the delivery of the remaining backlog of Boeing 737 MAX and increased deliveries of the Boeing 787 "Dreamliner," whose production remains below scheduled rates (Asian Aviation, 2023). Similar to the Boeing 737 MAX, the FAA reported quality issues with the company's Boeing 787, which impeded their delivery to customers. Furthermore, Boeing had to compensate purchasers of Boeing 787 aircraft for a year's delay in delivery (Isidore, 2023). Boeing acknowledged the problem and subsequently declared that it would rectify the production defects affecting the delayed 100 Dreamliner aircraft before delivery (Reid, 2023) and that it might postpone the delivery of 400 Boeing 737 MAX aircraft, each scheduled for 2023 (Attarwala, 2023). Due to grounded Boeing 737 MAXs and undelivered Boeing 787 "Dreamliners," Boeing has lost $383 million in continuing spending to fix the problems, which are facing uncertainty in deliveries (Gates, 2023). Following to several literature reviews and scientific analyses of the fields involved in practical application, the main challenges consist of management in supply chain loops. Boeing's subcontractors face numerous challenges in sourcing raw materials and components for aircraft assembly from various countries. Innovative advancements have exposed numerous electronic devices to software applications that impact the delivery of aircraft to clients.

Commercial air transportation is experiencing rapid growth and is now servicing innovative new-generation aircraft models. In the context of modernizing fleet availability, many leading global airline companies have prioritized the purchase of new models of the Boeing 737 MAX and Boeing 787 family, with the aim of reducing overall operating costs and ensuring their customers receive high-quality services on these ultra-modern aircraft. However, the airlines have placed orders for these aircraft, which the manufacturer often struggles to deliver within the scheduled time frame. Meanwhile, a delay in the intended period results in significant losses for the company, which in turn necessitates significant compensation for its customers. In reality, the high volume of orders for commercial aircraft can lead to significant financial risk for leading manufacturers, and this remains the primary factor (Richardson, 1969). To lower the risk associated with financial performance, it is necessary to predict innovation failures and, meanwhile, identify critical success factors of novel products offered to customers (Ernst, 2002).

Table 1. Boeing Airplanes Orders and Deliveries (Boeing, 2023)

Model	Minor Model	Gross Orders	Deliveries	Unfilled Orders
737	737-800	5,455	5,012	2
	737-800A	191	175	16
	737-7	386	0	358
	737-8	5,154	998	2,799
	737-8-200	462	127	334
	737-9	420	206	118
	737-10	1,071	0	963
767	767-2C	138	81	57
	767-300F	279	239	41
777	777-300ER	880	832	5
	777F	350	258	60
777X	777-8	43	0	8
	777-8F	55	0	55
	777-9	322	0	300
787	787-8	668	395	29
	787-9	1,341	606	570
	787-10	278	92	151
Total		17,493	9,021	5,866

Implementing new technologies, transitioning from a vertical supply structure to a multinational operation, and strengthening regulatory compliance have created challenges in supply chain management. Therefore, Boeing must take immediate and effective steps in communication to identify the necessary solutions to address issues during program development and production (Gordon, 2006; Behrens, 2010; Mayer, 2014).

This study is crucial as it aims to warn leasing organizations and airlines ordering aircraft from the Boeing company about the potential delays in delivery. This should prompt them to reevaluate their purchase agreements and address any gaps in the terms to prevent future disruptions to assigned flight schedules. The investigation has identified the primary issues with technological failure and supply chain management, which significantly contribute to delays on aircraft production lines. Therefore, the study aims to analyze and identify the financial losses incurred by the Boeing company in the event of a scheduled delivery deviation, as well as its impact on production processes.

1.1 Review of the Literature

Many studies attempt to analyze the unsuccessful confluence of programs dedicated to Boeing 737 MAX and Boeing 787 "Dreamliner" projects. Some authors focused on the investigation of Boeing 737 MAX crashes to find the root cause of the accidents; others concentrated on finding ongoing delays in the delivery of Boeing 787, identifying critical factors, and related risks.

Tzu-Ching (2007) found that Boeing's new supply chain model for the 787 Dreamliner program diverged from its previous experience, while Airbus relied on its major suppliers for the Airbus A380 program, who exercised much greater and more intensive control. Despite making significant capital investments and exerting considerable effort, Boeing continues to experience a series of delays in the delivery of its aircraft to customers.

Tang et al. (2009) found that an inappropriate management team, a lack of coherent strategies, and a lack of effective proactive risk assessment were the root causes of the problems. The study conducted by Mocenco (2015) sheds light on a number of factors related to the supply chain management of the Airbus A350XWB and Boeing 787 "Dreamliner" aircraft programs. The study's results show that changes in strategic and organizational models led to more outsourcing, which hurts performance, dependability, and financial stability.

In addition to the risks associated with outsourcing, Sodhi et al. (2012) identified other effective solutions to reduce the risks associated with supply chain management. Based on past mistakes, these solutions offer four recommendations to address the current issues Boeing is facing. According to Schmuck (2021), the design stage and assembly processes for the Boeing 787 faced significant challenges due to numerous innovation implementations and labor and management risks, which resulted in the first aircraft delivery occurring three years later than scheduled. The author argues that the major challenge was managing the global supply chain and ensuring quality integration. Digitization and improved supply chain quality contributed to the development and production process through the Boeing 787 "Dreamliner" project.

Woo et al. (2021), focusing on an analysis of the competitive actions of Boeing and Airbus, concluded that hard pressing on behalf of Airbus pushed Boeing to reconsider the business diversification options and risk-taking culture.

The study by Kuczynski et al. (2021) that looked into the accidents and the Boeing 737 MAX supply chain mishandling found a serious problem that was caused by a lack of leadership from central authority and a focus on making money for the company at the expense of public safety. Critical reasons refer to the inevitable and possible occurrence of crises in any stage of production and organizational processes.

The study by Imad et al. (2021) looked at two Boeing 737 MAX accidents from the point of view of how to communicate and manage a crisis. The results convinced Boeing to create a crisis management framework to handle tough situations and unexpected risks. Openness and integrity to share information with media groups and the public create confidence (Coombs, 2010); unfortunately, after the double crashes of the Boeing 737 MAX, Boeing hid the transparency and has faced several productions and setbacks (Chakrabarty and Bass, 2013).

According to Camble et al. (2023), the accidents involving the Boeing 737 MAX are not solely due to technical issues in the system or proactive pilot actions, but also to inappropriate leadership within an organization that prioritizes profitability over safety. Referring to the pilot’s comments, Sumner (2019) reported that on both flights, except for the Maneuvering Characteristics Augmentation System (MCAS), which dealt with the sensor angle of attack, we had issues with maintenance, pilot practices, training, and the costs and benefits of the flights.

Meanwhile, Boeing has failed fully, attempting to avoid the responsibility, leaving it to the customers and local authorities to ground the aircraft (Matthews, 2019). In turn, Palmer (2020) called this approach unstable communications, weak in crisis management, and critical behavior on behalf of the Boeing company. In spite of common accusations against Boeing, the novel technological complexity applied in the aviation industry carries a high degree of technical and managerial risks and financial uncertainty. Identifying priorities and critical success factors is vital at the beginnings of innovation projects (Jelac and Boljevic, 2016).

1.2 Factors and Reasons of Negative Effect on Aircraft Delivery

The aviation industry is the most vulnerable sector, requiring permanent development with innovative implementation. Boeing's concept, which applies intelligent technologies to design new generation aircraft types, contributes significantly to operator savings, reduces environmental degradation, and ensures societal satisfaction. Achievements in the development of new products enable the company to maintain its competitiveness over the long term, but they also introduce high risk, complexity, and uncertainty into the production processes. Therefore, a key approach is mandatory to identify potential challenges and critical reasons in the stage of beginning the idea generation and its future implications, which Boeing faced in the production of the Boeing 737 MAX and Boeing 787. The company's non-compliance with the scheduled delivery of the new generation aircraft, the Boeing 787 “Dreamliner”, and two crashes of the Boeing 737 MAX resulted in a negative reputation and significant financial losses. The Boeing 737 MAX was grounded and the Boeing 787 production process was extended, which ultimately caused the delivery to be three years later than planned. This was because potential risks and critical factors were not properly identified during the innovative production process, and there was not enough comprehensive supply chain management.

Table 2. Supply chain management solutions between Boeing and Airlines

Boeing	Airlines
High quality supply chain management structure	Sufficient stock availability of AOG parts
Avoid of risk-sharing suppliers	Raw materials and consumables for scheduled and unscheduled maintenance
To manage the complex programs for stock availability	High financial investment for offered RSPLs
Immediate stock planning of new components	Order tracking
To perform effective training program	Information sharing between planners and suppliers
Proper logistic Management and expand workforce	Periodic training plan
To conduct periodic quality audit	Upgrade the supplier list
Multi-channel communications with vendors	Availability of tools and ground equipment
Improvement of the delivery deadline	

Numerous airlines and leasing companies have declined purchase orders and terminated agreements because they lack confidence in the suitability of new products. The Boeing 737 MAX air crash was caused by a defect in an aircraft part, and in addition to the airline, the aircraft manufacturer also bears liability, as the aircraft was operated under an airworthiness warranty. In addition, the company lost USD 30 billion in its market value, and shareholders brought a class action lawsuit because of the loss of shares' value (Konert, 2019). Collings et al. (2022) discovered that the Maneuvering Characteristics Augmentation System (MCAS) software, which is in charge of keeping the pitch stability, was linked to both fatal accidents. Focusing on competitions with the Airbus A320 Neo, Boeing faced financial pressure, which led to a heavy reliance on the completion of the 737-MAX program (Cioroianu et al., 2021).

The manufacturer is responsible for approximately ten percent (10%) of the assembly of the Boeing 787 aircraft, which consists of approximately 4 million parts and components. The fact that the distribution of most component which production facilities is spread out among 40 partners around the world makes for a weak global collaborative supply chain environment (Xu et al., 2021), which in turn affects the productivity of the B787 production line. The tightening and overloading of the work schedule resulted in production organizational issues. This was followed by delays in receiving parts from both internal and external suppliers from different countries. Technical issues during functional tests included incomplete software and defects in control and power systems. The test flight results showed negative effects, leading to the postponement of the first delivery. In addition to the technical challenges encountered during the production process of the Boeing 787, the organization's human factors significantly contributed to dissatisfaction with the contract conditions (Jelac and Boljevic, 2016). The implementation of new-generation aircraft, with a modified composite body fuselage and electronic fuel flow control units, AS WELL AS a fly-by-wire navigation system, creates some complexity for the aircraft Original Equipment Manufacturer (OEM) by providing a spare part in a timely manner for their customers. The development of new approaches is necessary to minimize losses in the supply chain and delivery process. Table 2 shows several implementations that can contribute to mutual collaborations and increase the supply performance. Meanwhile, it avoids the unexpected financial costs and savings associated with supply management.

Despite numerous proposed and implemented solutions and diligent efforts to minimize risk, Boeing continued to experience incomplete orders, leading to financial losses. The following sections attempt to analyze the financial losses resulting from postponed delivery and describe the estimated sum of customer reimbursements.

The structure of the paper is as follows: Section 2 introduces a Method, Section 3 consists of the result and discussion, and finally Section 4 represents a conclusion.

2. Method

2.1 Data Collection

The empirical analysis uses official statements from Boeing to collect the number of aircraft sold from 2010 to 30 November 2023. Given that the OEM and customer mutually adhere to the delivery schedule for other models, this study will concentrate on the remaining four types of aircraft. However, the preparation of data for analysis will be based on the selection of historical annual orders, the number of delivered aircraft, and the number of unfilled orders (Table 3). After the two accidents of the Boeing 737 MAX, a total of 7502 aircraft were purchased; the most customers rejected 1600 aircraft, and the purchase agreement was canceled.

Table 3. Aircrafts order status and unit price (Boeing, 2023)

Aircraft type	737 MAX	767	777	787
Orders (E.A)	6126	425	1403	1349
Delivered (E.A)	1376	314	887	1099
Unfilled order (E.A)	4526	111	516	744
Unit price (M/USD)	107.4	198.2	336.7	265.1

*Note: Due to a variety of aircraft configuration the price for each aircraft is indicated as an average.

2.2 Quantitative Analysis Method

This study is exploring the financial losses of the Boeing company in relation to delivery delays, which involve two aircraft types, mostly the Boeing 737 MAX and Boeing 787 Dreamliner. System configuration problems ensure pitch stability in the first aircraft, while the supply of components from third-party subcontractors accompanies the second aircraft. The model incorporates the late delivery issues of Boeing 767/777 aircraft to accurately identify economic downturns.

This study utilizes the quantitative analysis method to ascertain the optimal loss rate for Boeing, thereby identifying the current and future perspectives of ordered aircraft. Model development involves the use of mathematical models to represent real-time problems through a system of econometric (mathematical) formulas for statistical analyses. One must weigh the costs and benefits when choosing a suitable mathematical model. The next step involves relating the decision variables, which are controllable inputs, with either fixed or variable parameters, which are uncontrollable inputs. Generally, stochastic models are more difficult to analyze. However, the optimal solution for the model refers to the values of the decision variables that yield the mathematically best output. Therefore, applying the model can define the loss of price level returned by Boeing to meet customer requirements. On the other hand, the review contributes to defining future operational concepts and policy requirements to improve financial stability.

The relationship between the modeling of delivery losses and total revenues is stipulated in Eq (1), which is formulated using the function proposed as;

$$TO_{\frac{a}{c}} = \mathrm{f}\,(B_3 + B_6 + B_7 + B_8) \qquad (1)$$

$TO_{\frac{a}{c}}$, is aircraft production rate in period from 2010 to 2023, $B_3 + B_6 + B_7 + B_8$ identified as Boeing 737/767/777/787 aircraft types.

To investigate the total predicted income and impact of losses in long run, the proposed structured model will be chosen as follow;

$$P_{po} = (P_1 B_3 + P_2 B_6 + P_3 B_7 + P_4 B_8) \qquad (2)$$

P_{po}, is total profit gaining by company from sales according to delivery report and P_1, P_2, P_3, $and\ P_4$ are aircraft average sale prices,

$$TL_{uo} = P_1 A_3 + P_2 A_6 + P_3 A_7 + P_4 A_8 \qquad (3)$$

TL_{uo}, is total loss from unfilled aircraft orders, and A_3, A_6, A_7, A_8 are unfilled aircraft orders.

2.3 Methodology

The methodology based on the Quantitative Analysis approach, uses a mathematical model through a system of mathematical formulas.

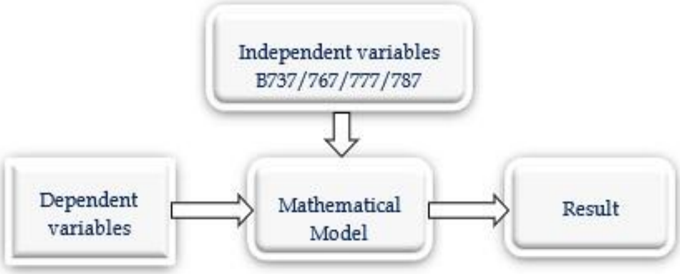


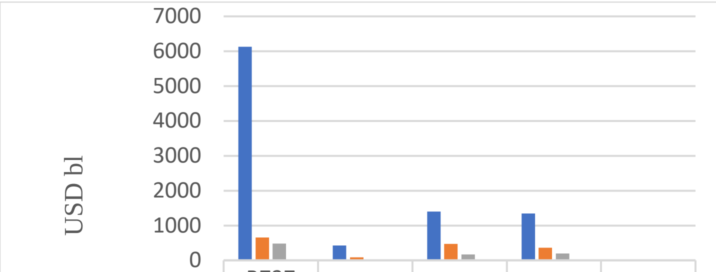
Fig. 1. Proposed methodology for the study

Dependent variables have been chosen the $TO_{\frac{a}{c}}, P_{po}, TL_{uo}$ while independent variables are representing the aircraft types with late delivery. Transforming the input data in model by testing and validation, the estimated result can be generated for accurate analysis. Therefore, the methodology formulated according to Figure 1.

The primary issues with the incompleteness of aircraft deliveries are mainly related to technological failure and supply chain management, which contribute to delays in aircraft production lines. Investigation of financial losses and the impact of late aircraft delivery were identified by relying on Boeing's reported document, which indicated the number of delays by aircraft type. Following the proposed methodology function, the estimated financial losses of the Boeing company have been calculated using the Quantitative Analysis Equations as stated in section 2.3.

3. Results and Discussion

Taking into account a variety of purchased aircraft types and postponing their delivery to potential customers is deemed a complicated problem due to the initially disrupted management process. The seller and buyer usually consider the mutually agreed estimated delivery schedule upon order placement; however, the manufacturer has failed to predict the associated risk level. In this case, proactive action could be taken upon implementing delivery schedules, thereby preventing unexpected violations and bearing penalties associated with delays. The lack of robustness during production planning has made the delivery schedule less sensitive to uncertain events that disrupt the process. Boeing's application of a robust optimization model for order assignment is currently unavailable due to a backlog of 5897 aircraft across four different types. Since 2010, multiple airline customers have placed total orders for the listed aircraft types, totaling 9303 aircraft valued at 657.9 billion USD for the Boeing 737 MAX, 84.2 billion for the Boeing 767, 472.4 billion for the Boeing 777, and 357.6 billion for the Boeing 787, totaling 1.6 trillion USD, as shown in Figure 2.



	B737 MAX	B767	B777	B787
TOa/c	6126	425	1403	1349
Ppo(USD bl)	657,9	84,2	472,4	357,6
TLuo (USD bl)	486,1	22	173,7	197,2
Penalty (USD bl)	11,3	0,177	1,29	1,86

Fig. 2. Boeing aircraft orders, deliveries, and unfilled order status presented in price equivalents

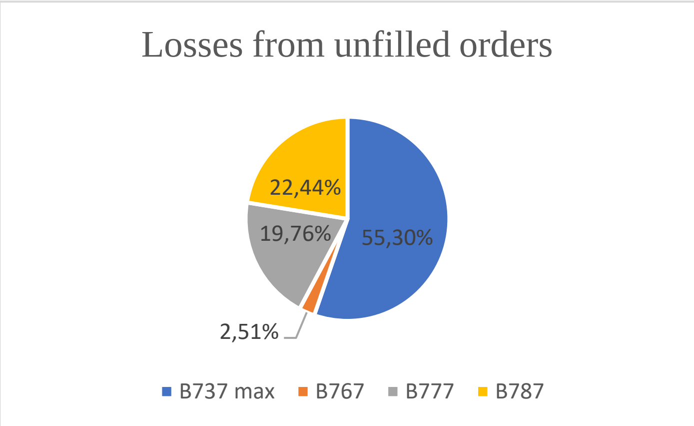


Fig. 3. The percentage of losses from unfilled orders by aircraft types

There is evidence that a special article in the contracts promises a delivery schedule of purchased aircraft by the year of date or consequence of next dates depending on the type and number of orders by customers. A separate clause in the contract outlines the late delivery condition, which is associated with penalty issues and order cancellation procedures. Boeing's significant delivery backlog has resulted in economic weakness for the company, leading to additional penalties. The number of incomes deducted associated with late delivery accounted for about 879 billion USD, nearly 55.3% of losses accumulated from the Boeing 737 MAX, Figure 3.

The industrial disruptions over the past years in the aviation industry associated with the delay in the delivery of commercial aircraft are brewing the compensation challenges for manufacturers. Blaming post-pandemic havoc in the supply chain, the aircraft manufacturer postponed delivery of new aircraft three to six months late. The number of compensations varies depending on the condition of the contract; however, typical exposure is for an inexcusable delay, which may reach 20K USD per outstanding day for single-aisle jets and may rise of USD 2–3 million per aircraft (CNBC, 2023). In this case, the total loss associated with paying penalties on behalf of Boeing to their customers can reach 14.7 billion USD for the coverage period of fulfilling the orders. Large leasing companies are exerting pressure on Boeing due to unexpected delays; additionally, airlines and other purchasers receive announcements and notifications about the upcoming delays. Purchase contracts contain detailed descriptions identifying excusable delays as "acts of God," which secure manufacturers from paying penalties for multiple types of delays. The term "non-excusable" refers to any delays that do not fall under the stated exclusive category. The grounding of the Boeing 737 MAX due to design defects was considered a significant non-excusable delay, leading to significant compensation payments from Boeing. That event may not promise cash flow at this stage because of extensions of delivery transferring to next year. There is an inverse relationship between aircraft delivery and airline profit, which means that excessive orders can lead to a decline in projected profit and incur airline loss (Jordan, 1998). The delayed delivery of Boeing 787 aircraft has persisted for over a year, resulting in penalty payments reaching 5.1 billion. As a form of compensation, many airlines have accepted the use of interim Boeing 767 aircraft (Anselmo, 2009). The Boeing 787 project promised a path to profitability, and its realization aims to increase production (Lu, 2010; Lu, 2013). However, the grounding of the Boeing 787 in 2013 once again focused not only on battery problems but also on other issues that came to light with the Critical Systems Review Team (CSRT) report (FAA, 2014; Pandian et al., 2020). Consequently, the delivery schedule had an impact, necessitating the rectification of shortcomings. Additionally, the recent fatal events involving the Boeing 737 MAX prompted designers to refocus their investigations on the reliability of the systems and operational features. According to several studies and polls of technical and quality staff working on the Boeing 787 project, the quality of this plane is not as good as was thought to be. To avoid problems with late deliveries, there are large-scale programs to improve the design performance of Boeing planes after safety and reliability. (Cole, 2019). Due to a supplier's quality mistake, manufacturing the fuel tanks has prompted Boeing to delay deliveries of Boeing 767 aircraft, which began following the recent resumption of the Boeing 787 Dreamliner deliveries after discovering an error in the structural parts. An earlier forecast to complete the certification of Boeing 777 family aircraft, which has been in development since 2013, was expected at the end of 2023; however, the plan faced delays because of certification queries from safety regulators. In spite of hard attempts, the delivery of the Boeing 777-9 and 777X is now postponed 2 years later, which is expected to start operation in 2025 (Oxborrow, 2022). Boeing has reported that in the first quarter of 2022, the revenue was $14.0 billion, driven by lower defense volume and partially offset by commercial services volume, while the net loss was $1.21 billion and the operating cash flow was about $3.2 billion, respectively. By increasing Boeing 737 MAX production and deliveries as well as valuable positive progress on the 787 project, partially offsetting the expenses, the revenue decreased by 4.2 billion USD (Thomas, 2022).

4. Conclusions

New projects invariably present new challenges, making it impossible to identify unanticipated potential risks until the project reaches its full-scale deployment. Initiating the idea could include making the business function more concrete, evaluating partners and subcontractors, testing new technology, and making sure that the right supply chain processes are in place. The Boeing 787 Dreamliner and Boeing 737 MAX programs have involved dramatic events as never before in the history of the company. Two crashes of Boeing 737s postponed the entry schedule to service of Boeing 787s, which indeed contributed to global problems in delivery, which even extended for 3 years, bearing penalties for customers and leasing companies. In addition to their diligent efforts to rectify the situation, Boeing continues to grapple with resolving ongoing issues related to certifications and sourcing suitable spare parts from suppliers. The Boeing 767 and Boeing 777 families have experienced delays due to issues in the supply chain, inadequate quality part manufacturing, and the impact of recent aircraft delivery delays. The persistent issues with delivery deadlines expose major airlines to the risk of ordering a large number of next-generation aircraft types, which can disrupt their flight management programs, particularly for long-haul destinations. However, financial losses of Boeing Company continue to be uncontrollable in the context of powerlessness to fix the situation, moreover making purchasers under big pressure and depriving them of satisfying their customer. Nevertheless, as indicated by the result of the study, apart from the managerial function, many aircraft have a challenge with the safety and reliability of the systems and components, which aircraft operations have been grounded for a long time period by the Federal Aviation Administration (FAA) and local aviation authorities of airlines. Global policy implications necessitate the involvement of design groups, legal authorities, and financial institutions in implementing appropriate measures to address the challenges that Boeing, a prominent aeronautical manufacturer, has encountered over the past few decades. In this context, future research is needed continuously in order to follow up behind the development of processes for improvement of the technological gaps and proper management supply chain challenges.

Nomenclature

$A_{3,}A_{6,}A_{7,}A_8$: Unfilled Aircraft Orders of Boeing 737/767/777/787 Accordingly

AOG : Aircraft on Ground

$B_{3,}B_{6,}B_{7,}B_8$: Identifies as Boeing 737/767/777/787 Aircraft Types

E.A : Each

M/USD : Million in US Dollars

MCAS : Maneuvering Characteristics Augmentation System

OEM : Original Equipment Manufacturer

$P_{1,}P_{2,}P_{3,}P_4$: Aircraft B737/767/777/787 Respective Average Sale Prices

P_{po} : Total Profit From Production and Delivery

TL_{uo} : Total Lost From Unfilled Order

$TO_{\frac{a}{c}}$: Aircraft Production Rate

CRediT Author Statement

Shahrzad Safaeimanesh: Conceptualization, Methodology, Software. **Tapdig Imanov**: Data curation, Writing- Original draft preparation, Validation, Reviewing and Editing.

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Research Article

Enhancing ATC Radar System Reliability: Strategies and Modern Solutions

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Abstract

This paper explores advanced strategies for improving ATC radar system reliability by addressing interference challenges from airborne systems such as ACAS, DME, and ADS-B, as well as environmental influences. Proposed solutions include the integration of autonomous receivers, hybrid radar architectures, and machine learning models for enhanced signal processing. Additionally, the paper examines innovative algorithms for real-time compensation of ionospheric distortions and atmospheric influences, ensuring precise long-range detection. The study demonstrates how modern techniques improve radar performance, reduce false alarms, and enhance detection accuracy. Future research should focus on integrating ADS-B and multi-positioning systems into ATC structures while optimizing compensation algorithms to ensure operational efficiency. The structural models considered in the work show that autonomous receivers are capable of detecting false alarms and thereby increasing the reliability of radar information, and hybrid radar systems effectively suppress interference and improve target tracking. Implementations of atmospheric compensation algorithms show promising results in minimizing errors caused by these factors. Additionally, machine learning applications have been shown to improve signal classification accuracy and adaptability in dynamic environments. The results obtained highlight the need to modernize ATC radar systems to address growing air traffic density and the growing prevalence of airborne interference sources. It is shown that future directions require studying the integration of new technologies such as ADS-B and multilateration into the ATC structure, optimizing ionospheric and atmospheric compensation algorithms, and conducting tests to validate these solutions. By addressing these challenges, the proposed methodologies ensure enhanced safety margins and operational efficiency for the aviation sector.

Keywords

ATC Efficiency
Radar Interference
Autonomous Receivers
Hybrid Radar Architectures
Machine Learning
Radar Reliability

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1. Introduction

Reliable radar functionality is a cornerstone of modern air traffic control (ATC) systems, ensuring safety and efficiency in increasingly congested airspace. However, ATC radar faces growing challenges due to interference from onboard avionics and environmental conditions. Electronic noise, environmental factors, and signal interference from aircraft avionics such as ACAS, DME, and ADS-B pose significant challenges to ATC radar

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performance. These interferences can result in false alarms, loss of radar signals, or complete system failure. Moreover, overlapping frequency bands, particularly at 1030 MHz and 1090 MHz, exacerbate these issues, leading to increased signal congestion and reduced reliability. For definitions of key terms and abbreviations used in this paper, please refer to the Nomenclature section.

Reliable radar functionality is critical not only for ensuring safety but also for optimizing operational efficiency within increasingly congested skies. Errors in radar perception and data processing can directly compromise ATC decisions, risking both safety and operational efficiency. The incorporation of automation and advanced technologies further underscores the need for robust radar systems to support real-time decision-making (Farina and Pardini, 1980; Shorrock, 2007; Perry, 1997).

Moreover, the interaction between radar signals and the ionosphere presents a significant challenge in the field of radar technology. This paper also explores the methodologies developed to mitigate these ionosphere effects, particularly focusing on long-range detection radars (Tersin, 2020).

Despite advancements in radar technology, current systems are vulnerable to various interferences. These interferences stem from both external environmental factors and signals generated by onboard systems. ACAS and ADS-B emit signals in frequency bands that overlap with secondary radar systems, resulting in false alarms, interference, and missed detections. In addition, interference from natural and man-made sources makes it difficult to identify legitimate targets, especially in high-traffic airspace (Haykin, 1991).

Traditional methods, including static filtering and basic signal-to-noise ratio (SNR) enhancements, have shown limited efficacy in mitigating these challenges. As air traffic continues to grow, the limitations of existing radar systems necessitate innovative approaches that enhance both reliability and accuracy. This study aims to analyze and evaluate advanced methodologies to enhance the reliability of ATC radar systems by mitigating interference from both natural and artificial sources. Specifically, we propose the integration of autonomous receivers, machine learning algorithms for signal classification, and hybrid radar architectures. These approaches address the growing complexity of modern airspace while ensuring high-precision tracking and interference suppression.

2. Method

2.1. Features of automatic processing of radar information to eliminate the negative influence of the atmosphere on the propagation of radio waves

This section outlines the methodology used to evaluate and mitigate interference effects on ATC radar systems. The study employs a multi-faceted approach, integrating experimental measurements, simulation-based analysis, and advanced signal processing techniques. The methodology consists of three primary components: evaluating the impact of environmental and onboard system interference, testing autonomous receivers and hybrid radar architectures, and applying machine learning techniques for signal classification and noise suppression. This study primarily focuses on a theoretical analysis based on a comprehensive literature review and simulation-based modeling. The proposed methodologies for improving radar reliability were evaluated using previously published experimental data and validated through computational models.

As is known, the Earth's atmosphere has a strong influence on the propagation of a radar signal. The troposphere is characterized by significant refraction caused by gradients in dielectric constant due to changes in temperature, pressure and water vapor content. This causes radar waves to be deflected and introduces attenuation, especially in adverse weather conditions such as rain and fog.

Above the troposphere, the interference zone, which lies between 20 and 50 kilometers, exhibits near-free-space conditions with minimal refraction effects. Beyond this zone, the ionosphere, extending up to 600 kilometers, contains ionized particles that cause significant phenomena such as refraction, absorption, polarization rotation, and noise emission. While these effects diminish at higher radar frequencies, they are critical at frequencies below 6 MHz and above 30 MHz. Near the Earth's surface, radar waves also experience diffraction effects, such as knife-edge or cylinder-edge diffraction, when encountering physical obstructions.

Refraction, in particular, is a critical phenomenon in radar wave propagation, arising due to variations in the atmospheric refractive index. This index, defined as the ratio of the electromagnetic wave velocity in free space to that in a medium, is mathematically expressed as:

$$n = \frac{c}{v} \quad (1)$$

c: the speed of light in free space

v: the wave group velocity in the medium

Variations in n with altitude result in bending radar waves downward, leading to angular errors in elevation measurements. The bending angle of radar waves can be modeled as proportional to the refractivity gradient, where h is the altitude. Additionally, in surface-level phenomena, conditions such as ducting can occur, especially over warm sea surfaces, where waves bend excessively and sometimes follow the Earth's curvature. These refractive effects are typically modeled using a stratified atmospheric approach, where the atmosphere is treated as layers with constant refractive indices. This model aids in estimating errors in range and time-delay measurements (Fig.1) (Mahafza, 2009).

Errors caused by the ionosphere can severely compromise radar accuracy. To mitigate such interferences several approaches, algorithms, and methods for processing radar data are available.

Each algorithm has its unique strengths and weaknesses, which are crucial for optimizing radar performance. Here's a brief overview of the existing algorithms:

- Automatic Processing Algorithms: These algorithms process radar data in real-time, enabling continuous adjustments to compensate for ionospheric effects.
- Compensation Algorithms: These algorithms correct signal propagation delays in long-range detection radars, improving measurement accuracy.
- Data Processing Algorithms: This category includes methods that analyze radar data in conjunction with information from auxiliary radio-electronic facilities. These algorithms aim to improve the overall accuracy of radar systems by integrating multiple data sources, thus providing a more comprehensive understanding of the ionospheric influence.
- Frequency-Specific Algorithms: The effectiveness of these algorithms can vary significantly depending on the frequency range of the radar system. Some algorithms are optimized for specific frequency bands, which can enhance their performance in particular operational contexts.
- Satellite Navigation Data Utilization: Some algorithms leverage data from navigation satellites (like GLONASS, GPS, and Galileo) to determine electron and ion concentrations in the ionosphere. This information is crucial for making informed adjustments to radar operations, ensuring that ionospheric effects are accounted for accurately.

When operating in the ionospheric analysis mode, the range of distances should cover the entire altitude range of interest from 90 to 600 km, which contains the most concentrated layers of the ionosphere. Since the most important directions for the radars considered in this work are the entire azimuth sector in the lower elevation angle (from 0.5° to 10° from the tangent to the Earth in the projection of the phase center of radiation onto it), the error correction must be carried out in this region of space. For the center of the lower elevation angle of the radars considered, with an average radius of the Earth Rz = 6371 km, the range of distances (from OA to OB, where OA and OB are boundary points shown in Fig. 2) will be from 1074 to 2830 km.

- Real-Time Compensation Algorithms: Innovative algorithms that enabled real-time compensation for ionospheric effects on radar signals. These algorithms were designed to function without the need for additional measurement tools, relying solely on the radar systems' inherent capabilities.
- Practical Implementation: Practical results from experiments were presented, demonstrating the successful application of these algorithms in long-range detection radars. (Tersin, 2020).

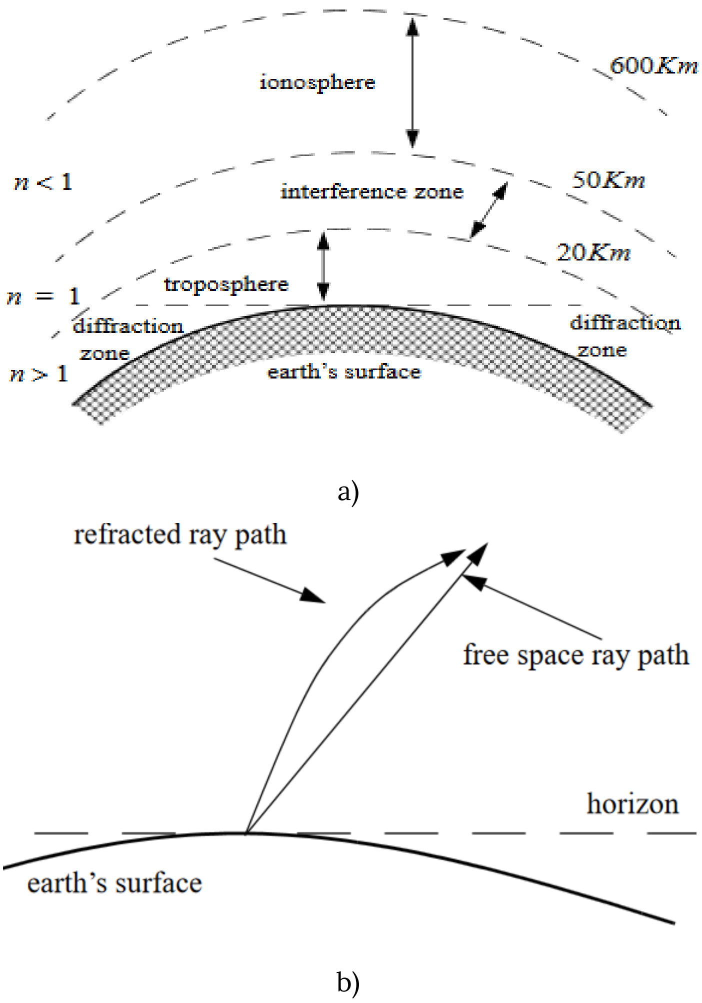


Fig. 1. Spatial structure of the earth`s atmosphere (a) and distortion of radio waves due to variations in the refractive index of atmospheric layers (b) (Mahafza, 2009)

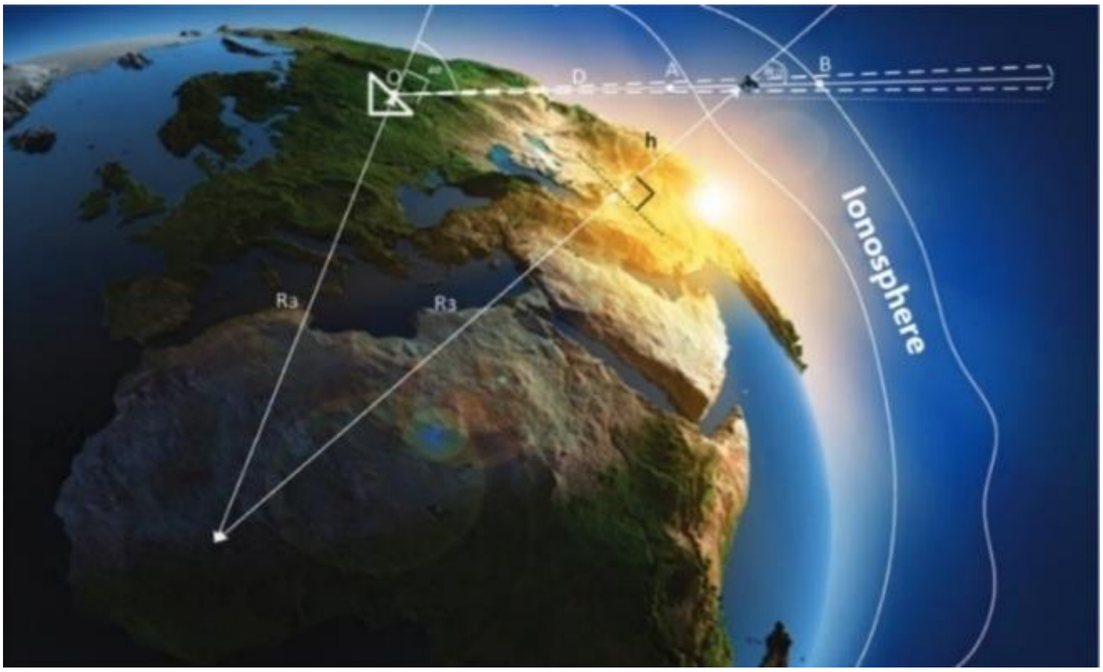


Fig. 2. Visualization of zenith angles and distances to the spacecraft (Logovsky, 2016)

2.2. Analysis of methods for processing radar information in conditions of signal-like interference

In conditions of signal-like interference caused by multipath propagation or signal retransmission, existing methods of processing radar information are not effective enough. This interference makes it difficult to distinguish true targets from false marks. The aim of the approach is to develop and analyze a simulation model that allows evaluating the efficiency of radar target selection using spatial separation of measurements from two spaced radars. The main focus is on processing radar information under conditions of signal-like interference.

Two key methods are used:

- Spatial separation of measurements: data from two separated radars is used for target selection.
- Comparison of target coordinates: the distance between the measured target coordinates of the two radars is calculated. If this distance (δr(t)) is less than a given threshold (μобн) the target is considered true (Fig. 3).

$$\delta_r(t) = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2} \quad (2)$$

(X_1, Y_1, Z_1) : the target coordinates measured by radar 1

(X_2, Y_2, Z_2) : the target coordinates measured by radar 2

C (target) : true position of the target

C_1 and C_2 : measured positions of the target by the first and second radars, respectively

S_1 and S_2 : measurement uncertainty regions

$\delta(t)$: distance between the coordinates measured by the two radars

Noise-like interference is random and uncorrelated with the radar's probing signal. Noise-like interference affects both radar stations independently. Due to the separation of radar 1 and radar 2, the measured coordinates of the same target remain consistent across stations, whereas false detections (due to noise) vary significantly. Spatial disparity (δ r(t)) helps filter out these inconsistent false alarms, improving the accuracy of detection.

Signal-like interference typically generates false marks that are spatially inconsistent across radar stations. By comparing target positions from both stations, the spatial analysis identifies and discards these inconsistencies, leveraging the fact that true targets align in measurements from both radar 1 and radar 2. The model's reliance on spatial analysis makes it highly suitable for real-world radar applications in complex environments, such as:

- Air traffic control, where signal reflections from terrain can mimic targets.
- Surveillance in environments with deliberate jamming (signal-like interference).
- Weather monitoring, where dense noise fields and reflections are common.

By combining spatial analysis with conventional detection techniques, the model significantly improves the probability of correct target detection while reducing false alarms caused by interference (Parshutkin, Levin, Galandzovskiy, 2020)

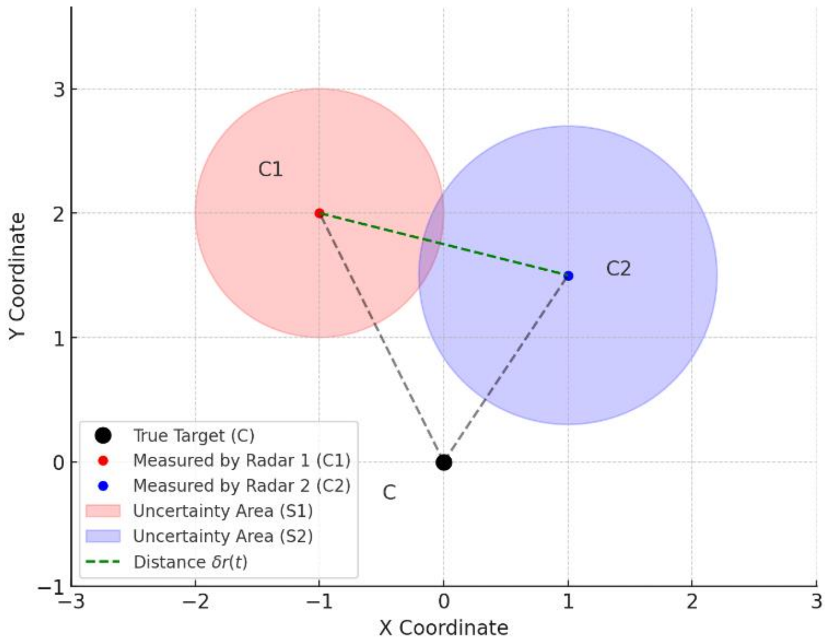


Fig. 3. Determining the coordinates of a radar target

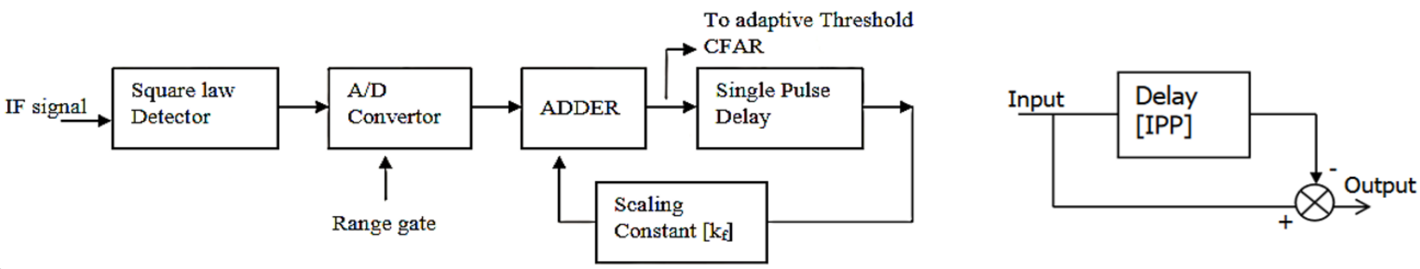


Fig. 4. Square-law signal detector (Etim, 2013)

2.3. Advancements in Digital Signal Processing for Modern Radar Systems

Digital Signal Processing (DSP) has revolutionized radar systems, providing tools to improve signal detection, reduce noise, and handle clutter. Radar works by transmitting electromagnetic waves and analyzing the echoes reflected by objects. These echoes contain information about the target's location, speed, and size. However, radar signals can be contaminated by noise, clutter (unwanted echoes from the ground or sea), and interference. DSP is the set of mathematical techniques applied to these signals to clean, enhance, and extract useful information (Fig. 4).

CFAR is a dynamic thresholding technique that helps distinguish real targets from clutter. It works by:

- Analyzing the background noise level in real time.
- Setting a detection threshold that adapts based on this noise level to avoid too many false alarms.

For example, in a busy airport, CFAR ensures the radar can detect aircraft without being confused by reflections from nearby buildings or vehicles.

DSP enhances SAR imaging, a technology used to create high-resolution radar images:

- SAR can produce detailed maps of terrain or objects, even in bad weather or through obstacles like clouds and smoke.
- DSP improves the clarity of these images by removing distortions caused by movement or environmental conditions.

DSP can make radar systems smarter, faster, and more reliable:

- Smarter: With adaptive algorithms that adjust to changing environments.
- Faster: By processing signals in real-time, enabling rapid decision-making.
- Reliable: Through techniques like CFAR that reduce false alarms and improve detection accuracy.

DSP in radar systems, addressing key challenges like noise suppression, clutter rejection, and speed measurement. The proposed methods are foundational for improving radar systems' performance, making them applicable across industries (Etim and Otu, 2013; Thurber, 1983; Li, 2024).

2.4. Interference caused by the frequency range and operating modes of secondary surveillance radar systems

Radar systems play a critical role in ATC operations by providing essential data on aircraft positions and movements. Advancements in radar data processing have significantly improved the capacity of these systems to handle complex traffic scenarios. Secondary radar systems, for instance, were introduced to address the limitations of primary radars by reducing clutter and enhancing identification accuracy (Farina and Pardini, 1980).

Modern radar systems face numerous challenges that compromise their reliability. Among these, interference from onboard systems like ACAS and ADS-B is particularly problematic. The critical impact of such interferences can disrupt ATC operations and reduce situational awareness (Flavio and Camargo, 2011).

Clutter remains another persistent issue in radar operations classified into environmental and system-generated categories, which pose significant challenges to signal detection (Haykin, Stehwien, Deng, 1991).

Regulation of the use of radiofrequency spectrum for radar surveillance systems is a complex and extremely important task in conditions of increasing air traffic intensity. Particular attention is paid to the 1030/1090 MHz frequency bands, which are the basis for the operation of key air traffic control and surveillance systems. This aspect requires constant monitoring, coordination, and implementation of innovative solutions to ensure the safe, efficient, and uninterrupted functioning of the aviation industry. The following systems use this band:

1. Mode A/C radar transponder.
2. Mode S radar.
3. Distance Measuring Equipment (DME).
4. Automatic Dependent Surveillance-Broadcast Technology.
5. Multilateration System.
6. Airborne Collision Avoidance System (ACAS) (Dessì, 2021).

Radar signals are used by the ACAS to identify nearby aircraft and provide pilots with resolution alerts to prevent collisions. ACAS's radar emissions, however, have the potential to disrupt other radar systems, including those utilized by Air Traffic Control (ATC). False warnings, a loss of radar returns, or even complete radar failure can result from this interference (Zaidi, 2023).

One of the most significant contributors to radar interference in ATC systems is the transmitter of the ACAS. This overlap can result in the detection of non-existent targets or the failure to track actual aircraft, leading to erroneous. Specifically, the transmission of Resolution Advisory (RA) signals by ACAS can produce false echoes on ATC radar displays, further complicating traffic management (Aliyev and Isgandarov, 2023).

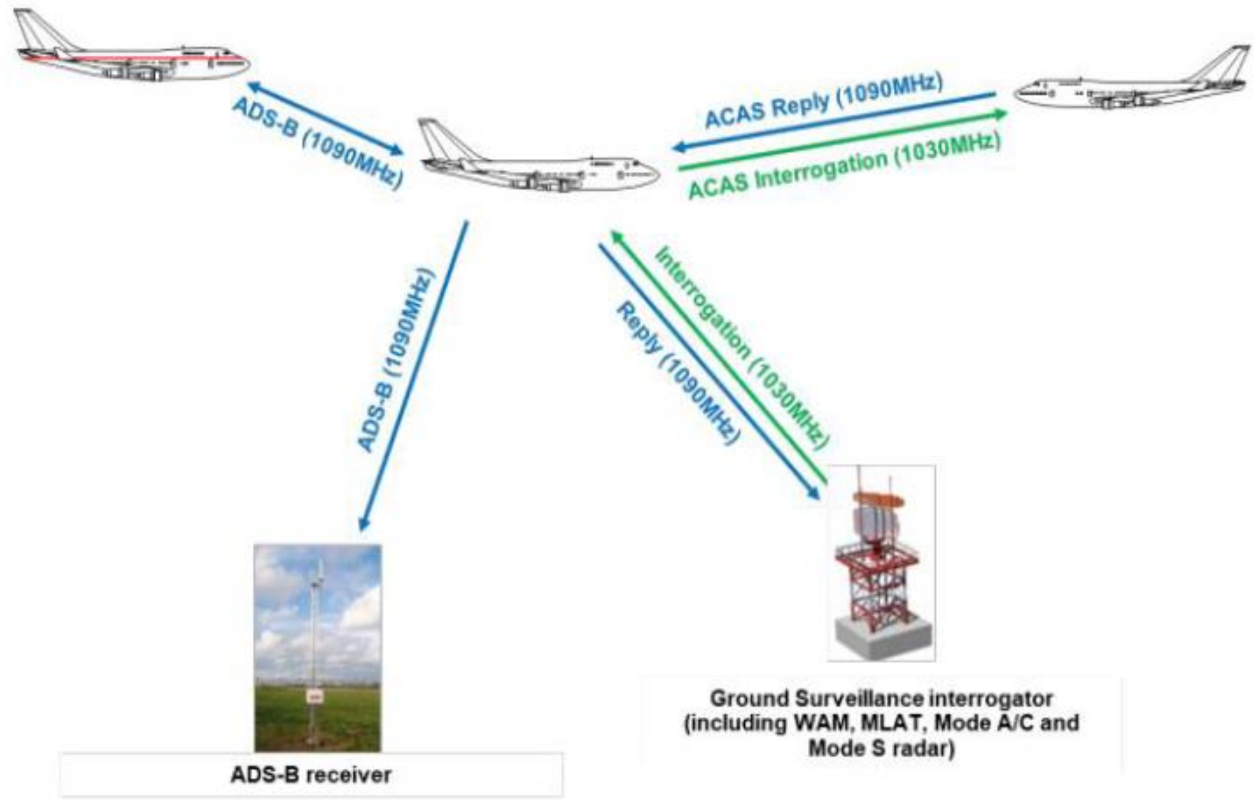
Another issue arises from the high power output of the ACAS transmitter, which can saturate the ATC radar receiver. This overload may impair the radar's ability to process incoming signals accurately, resulting in temporary or complete loss of target tracking.

The ACAS receiver also contributes to operational challenges. Designed to detect signals in the 1090 MHz frequency band receiver may misinterpret radar signals, identifying false targets or misrepresenting genuine radar data. The potential for interference increases when two aircraft equipped with ACAS are in close proximity, as their surveillance ranges overlap. This can lead to mutual interference, degrading the overall effectiveness of both systems and causing unnecessary alerts (Fig. 5).

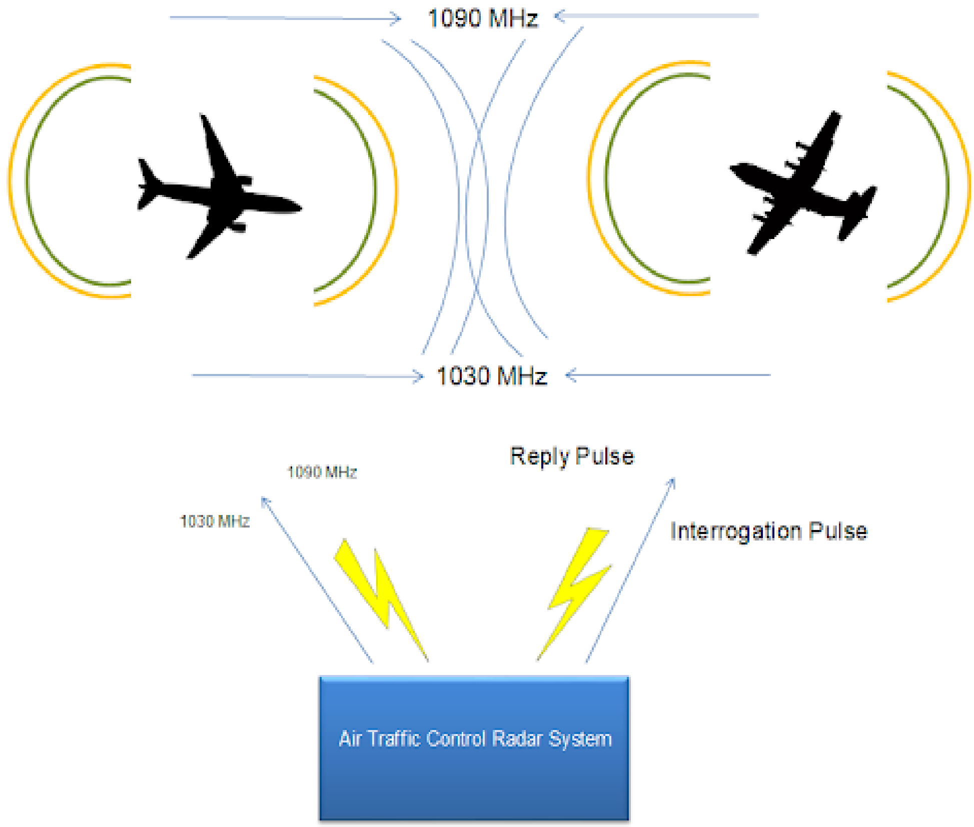
2.5. Analysis of the current situation with congestion in the 1030-1090 MHz range on the example of the JFK airport

To identify the congestion of the 1030-1090 MHz frequency band, aircraft takeoffs and landings at John F. Kennedy International Airport (JFK) are analyzed from 1030/1090 MHz systems and radar data we can understand the following (Fig.6):

- Data Sources: The analysis utilized recordings from the 1030/1090 MHz systems and radar data from the Mode S radar at JFK airport. This combination allowed for a comprehensive understanding of aircraft movements during the observation period.
- Identification of Takeoffs: To identify aircraft taking off, the study applied specific filters based on range and altitude. The aircraft were considered to be taking off if they were located near the airport and exhibited an increasing range rate from the airport over the duration of their flight track.
- Identification of Landings: Similarly, landing aircraft were detected by monitoring their tracks, which ended at the airport surface. The analysis confirmed that these aircraft showed a decreasing range rate on average as they approached the airport.
- Purpose of the Analysis: The overall goal of this analysis was to construct a timeline of aircraft operations at JFK airport, which would help in understanding the traffic patterns and operational efficiency of the airport during the observation period.



a)



b)

Fig. 5. Use of the 1030-1090 MHz band: a) by various systems (Dessì, 2021); b) Potential interference interactions between ACAS and ATC services (Zaidi, 2023)

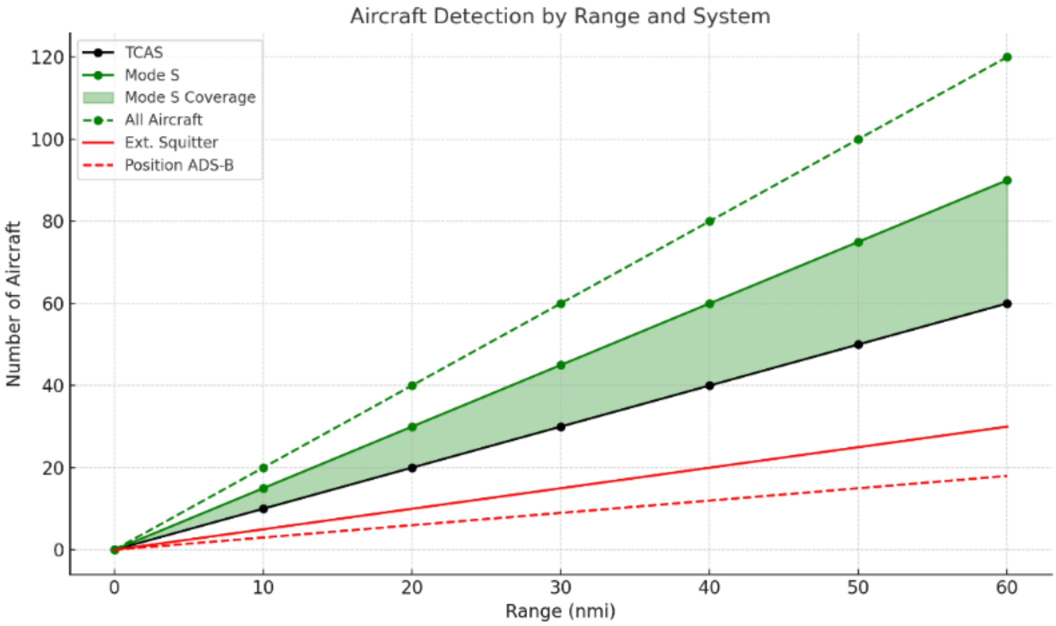


Fig. 6. Spatial distribution of aircraft by distance from a given reference point (e.g. JFK airport)

In summary, the 1030-1090 MHz frequency band is heavily utilized by various critical aviation systems, and the expected increase in traffic due to regulatory mandates highlights the need for careful management to mitigate overload and ensure safe operations.

Continuous monitoring of the 1030/1090 MHz frequency band is essential to address the overload and its consequences. The paper highlights the importance of using detailed data from 1030/1090 MHz monitoring to understand unusual encounters and improve coordination. This data can help identify patterns and potential overload situations, allowing for timely interventions (Panken, 2012).

Cumulative Aircraft Count: Figure 6 shows a cumulative count of aircraft as a function of distance from the radar source, which is typically located at JFK. This aligns with the observation that the cumulative number of aircraft grows linearly with range, at a rate of about 3 aircraft per nautical mile (NM) away from the radar.

Uniform Distribution: The data may indicate that the distribution of aircraft is approximately uniform in range, meaning that as you move away from JFK, the density of aircraft remains relatively consistent. This is supported by the finding that the local density of aircraft is higher near JFK and diminishes as the distance increases.

Vertical Spacing: The vertical spacing in figure 6 could represent the number of aircraft detected at various ranges. If the spacing is approximately uniform, it suggests that aircraft are distributed evenly across the range, although this may not reflect their actual distribution in the airspace.

Line-of-Sight Limitations: The figure may also highlight the limitations of radar detection, particularly at longer ranges and lower altitudes. For instance, aircraft at long ranges and low altitudes may fall below the radar's line of sight, which is a critical factor in understanding the data presented.

Implications for Air Traffic Management: Understanding the range distribution of aircraft is crucial for air traffic management and safety. It helps in assessing the effectiveness of radar systems and the potential for collision avoidance, especially in high-density areas like JFK.

In summary, figure 6 provides a visual representation of the range distribution of aircraft, illustrating how aircraft density varies with distance from JFK Airport. It emphasizes the uniform distribution of aircraft within a certain range and highlights the limitations of radar detection, which are essential for effective air traffic management and safety protocols. The insights are vital for understanding aircraft behavior in busy airspaces.

2.6. The Consequences of Spectrum Overload on ATC Surveillance Systems

The dual interference pathways—through both the transmitter and receiver—pose significant risks for ATC operations:

- False Targets: Cluttered radar displays due to phantom signals from ACAS transmitters.
- Signal Loss: Overloaded receivers fail to track real targets effectively.
- Operational Confusion: Mutual ACAS interference between aircraft generates conflicting or redundant advisories, increasing pilot and controller workload.

These issues underline the need for improved spectrum management and the integration of interference-resilient systems into ATC operations (Zaidi, 2023).

Spectrum regulation in Europe is based on documents such as the Surveillance Performance Interoperability Implementation Rule (SPI IR). These standards require the implementation of harmonized measures among all Member States to minimize the negative impact on the frequency range. Harmonization of regulatory approaches at the level of the entire region plays a key role in the creation of a resilient surveillance system. This includes both technical measures to reduce spectrum load and organizational measures to ensure the consistency of the use of systems in different countries (Civil Aviation Authority [CAA], 2024).

A poor radio frequency environment may lead to the need to deploy more surveillance sensors to maintain the required performance level (e.g. additional ADS-B stations) or to use other technical systems operating on a different radio frequency. One of the objectives of the SPI IR rules is to maintain the performance of the 1030 MHz and 1090 MHz frequencies in the Single European Airspace, thereby avoiding the need to introduce new surveillance radio frequencies (Maggıore, 2021; CAA, 2024).

Excessive interrogations refer to repetitive or high-frequency signals sent by surveillance systems to aircraft transponders that exceed their minimum operational threshold. This can result in the following:

- Increased transponder loading: Transponders can become overloaded, reducing their ability to process incoming signals effectively.
- Limited response signals: Transponders may not be able to respond to all interrogations if the loading exceeds their design capabilities. This is critical as it directly impacts the reliability of surveillance systems.
- Potential system failures: Excessive interrogations can cause unexpected failures in transponders designed only to meet ICAO minimum standards.
- Distortion: If a receiver has a large number of aircraft transponders in range, the large number of responses will cause interference and distortion. The receiver will have difficulty decoding the responses. Omnidirectional antennas are more susceptible to distortion than rotating antennas with a narrow beam.
- Query conflict: If the number of queries sent from different surveillance interrogators is excessive, the queries arrive simultaneously and the transponder responds to only one of them (CAA, 2024).

3. Results and Discussion

3.1. Analysis of the possibilities and prospects of proposed new solutions

This section is devoted to the development of proposed measures aimed at increasing the reliability of radar systems used in ATC. The methodology implies the use of autonomous receivers, combined radar schemes and machine learning tools, which will help cope with such problems.

Significant advances in the field of radar signal processing include spatio-temporal adaptive processing (STAP). It combines spatial and temporal filtering, effectively suppressing interference, especially from moving objects. However, practical implementation of STAP in real ATC environments is hampered by high computational complexity. Incorporating machine learning techniques into radar systems opens up new prospects for improving their reliability. By training algorithms to recognize signals based on characteristic features and patterns, it becomes possible to adapt to a variety of interference situations without the need for detailed pre-tuning. (Pozesky and Mann, 1989).

Figure 7 illustrates the filtering process, where the space-time adaptive method significantly reduces interference and improves signal clarity. By leveraging spatiotemporal filtering techniques, the system can efficiently suppress clutter and enhance target detection in complex ATC environments. The clutter Doppler frequency depends on the cone angle, making true space-time filtering essential for effective clutter suppression. Figure 7 illustrates this, showing clutter spectral power for a side-looking array antenna plotted against the cosine of the azimuth (ϕcos) and Doppler frequency (Df). The clutter spectrum appears as a diagonal ridge, modulated by the transmit beam (Aliyev and Isgandarov, 2024).

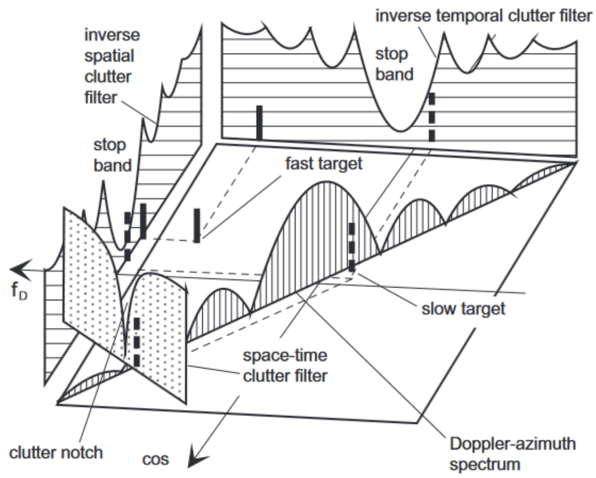


Fig. 7. Fundamentals of spatiotemporal noise filtering (Bürger, 2006)

To effectively mitigate radar clutter and preserve target detectability, different signal processing techniques are employed. The following approaches illustrate key methods used in clutter suppression:

- Temporal processing cancels the clutter spectrum's projection onto the Df axis using an inverse filter. However, this causes slow targets to be attenuated because the clutter notch is aligned with the transmit beam's Doppler response.
- Spatial processing projects the clutter spectrum onto the ϕcos axis. While inverse spatial filters suppress clutter, they create a wide stop band, making the radar blind in the look direction, affecting both fast and slow targets.
- Space-time processing leverages the clutter spectrum's narrow ridge-like structure. A space-time filter forms a narrow clutter notch, preserving even slow targets in the pass band (Bürger, 2006; Velikanova, 2014).

3.2. Justification for the Potential Application of the Kalman Filter in Signal Processing for ATC Systems

Data processing in electronic systems is usually carried out using information about input signals and interference, parameters of measuring devices, and also about the aircraft movement. This prior knowledge is represented through mathematical models that describe signals, interference, and device characteristics. In the case where the hypothesis of a constant rate of change of phase coordinates for estimating range and speed is accepted, a linear state model can be written as a vector-matrix equation:

$$\begin{cases} [X(k)] = [\Phi] \times [X(k-1)] + [\Gamma] \times [\xi_X(k-1)] \\ \begin{bmatrix} D(k) \\ V(k) \end{bmatrix} = \begin{bmatrix} 1 & \tau \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} D(k-1) \\ V(k-1) \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \times \begin{bmatrix} \xi_D(k-1) \\ 0 \end{bmatrix} \end{cases} \quad (3)$$

in algebraic form:

$$\begin{cases} D(k) = D(k-1) + V(k-1) + \xi_D(k-1) \\ V(k) = V(k-1) \end{cases} \quad (4)$$

$D(k)$: range to the aircraft

$V(k)$: aircraft speed

τ : sampling interval

ξ_D : disturbance noise, taking into account atmospheric turbulence, and uneven thrust of aircraft engines (Panasyuk, 2016).

For signal filtering in air traffic control systems, the Kalman filter is used to estimate the state x_k e.g. the actual radar signal) based on observations z_k, which contain noise. The Kalman filter formulas involve two main steps:

1. Prediction stage:

At this stage, a priori estimates of the state and covariances are calculated:

$$\widehat{x_{\bar{k}}} = A_{\hat{x}_{k-1}} + B_{u_k} \quad (5)$$

$$P_{\bar{k}} = AP_{k-1}A^T + Q \quad (6)$$

A : state transition matrix (describes the dynamics of the system)

B : control matrix

u_k : control vector

Q : process noise covariance matrix.

2. Update stage (correction):

At the update stage, estimates are refined based on new measurements:

$$K_k = P_{\bar{k}}H^T(HP_{\bar{k}}H^T + R)^{-1} \quad (7)$$

$$\widehat{x_k} = \widehat{x_{\bar{k}}} + K_k\left(z_k - H_{\hat{x}_{\bar{k}}}\right) \quad (8)$$

$$P_k = (I - K_kH)P_{\bar{k}} \quad (9)$$

K : Kalman coefficient (update weight)

H : measurement matrix

R : measurement noise covariance matrix

z_k : current observation

1. State model:

The state (x_k) is taken as the target object parameters, such as signal frequency, delay and intensity.

2. Measurement update:

Observations (z_k) are received signals containing a mixture of TCAS and ATC. The measurement noise (R) is due to the frequency overlap in the 1030/1090 MHz bands.

3. Processing:

- Using a priori estimates ($\widehat{x_k}$) and Kalman coefficients (K_k), the filter corrects the signal, suppressing TCAS noise and extracting reliable ATC data.
- Adaptive update (K_k) allows the filter to work effectively in real-time.

3.3. Autonomous receivers for detecting false decisions in ATC radars and developing recommendations for eliminating interference

One of the primary issues in radar systems is interference caused by signals from onboard systems like ACAS. To address this, we propose the integration of standalone autonomous receivers that operate parallel to existing radar systems.

Design Principles are as follows:

1. Dedicated Frequency Monitoring: These receivers continuously monitor the frequency ranges commonly affected by ACAS signals.
2. Signal Isolation and Analysis: Using digital signal processing (DSP), the receivers differentiate between legitimate radar returns and interference.
3. Decision-Making Algorithms: The isolated signals are processed by decision-making algorithms to assess their origin and relevance to ATC operations.

Implementation Strategy:

1. Autonomous receivers are designed to complement both primary and secondary radar systems.
2. The output from these receivers is fed into a central processing unit for integration with radar data, allowing for a holistic analysis of detected targets.
3. Real-time feedback mechanisms enable immediate suppression of false alarms.

Advantages:

1. Significant reduction in false alarms caused by overlapping frequencies.
2. Enhanced ability to identify and classify legitimate radar returns.

To enhance ATC reliability and efficiency, autonomous detection systems are crucial. The proposed system features an independent detection scheme centered on a digital processing unit with memory and threshold devices for autonomous decision-making. In the SSR signal detection process, each observation compares the signal against upper and lower thresholds, set by target miss and false alarm probabilities. Signals exceeding the upper threshold confirm a target, while those below the lower threshold rule it out. Signals within the thresholds prompt further observations, extending the input vector (Fig. 8).

Using the logarithm of the likelihood ratio simplifies computations by replacing multiplication with summation. Statistics accumulate sequentially until a threshold is reached, stopping the process and finalizing the decision. This approach resembles an incoherent accumulation of optimal processing results. The scheme filters noise and improves detection accuracy, relying on statistical methods to ensure reliable target identification. The digital processing unit, integrating memory and threshold functions, enables autonomous and precise operation

Machine learning (ML) techniques offer a dynamic and adaptive approach to radar signal processing. These models can be trained to classify signals, detect patterns, and predict interference scenarios (Aliyev and Isgandarov, 2024).

One of the most significant advances has been the integration of autonomous receivers into radar systems. These devices play an important role in reducing the false alarm rate, which is one of the main problems with traditional radar systems. The improved ability to separate true signals from interference allows autonomous receivers to significantly reduce the number of false alarms. Autonomous receivers also stand out for their high signal isolation accuracy, which improves the quality of target detection and tracking. This allows the radar system to quickly and accurately respond to changes in the environment, which is especially important for areas where high responsiveness is required, such as air traffic control or military defense systems.

Another major development is the use of hybrid radar systems, which integrate both primary and secondary radar data to enhance detection capabilities. The hybrid approach also incorporates adaptive filtering techniques, which are designed to minimize errors caused by clutter. This filtering process ensures that the radar system can focus on legitimate signals, ignoring unwanted interference from the environment. By cross-referencing information from different radars, the system can determine the exact location of a target with greater precision, offering a more comprehensive and reliable tracking solution.

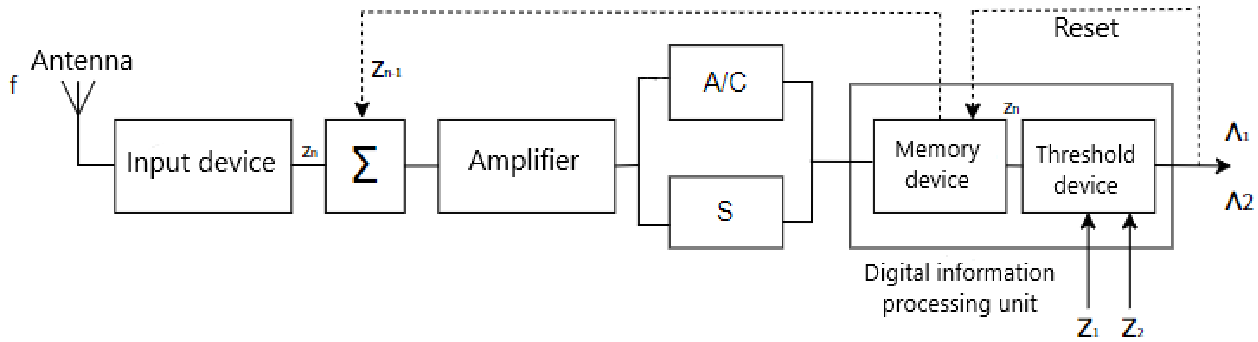


Fig. 8. Block diagram of an autonomous device for detecting a secondary radar signal

Table 1. A comparative analysis of the three proposed solutions highlights their relative strengths and limitations

Solution	Strengths	Limitations
Autonomous Receivers	High reduction in false alarms; Minimal latency	Limited scalability for very high-density scenarios
Hybrid Radar Systems	Superior clutter suppression; Improved positional accuracy	Increased complexity in system integration
Machine Learning Models	Adaptive and accurate classification; Scalable processing	High computational demands; Dependence on training quality

In addition to these hardware improvements, the use of machine learning (ML) models has become a pivotal component of modern radar systems. Machine learning algorithms are particularly effective in tasks such as signal classification, clutter reduction, and interference prediction. By training on past radar data, these systems learn to distinguish between legitimate radar returns and various forms of interference, ensuring that false positives are minimized. One of the strengths of ML models is their adaptability.

Online learning algorithms allow these systems to adjust to new interference patterns as they emerge, ensuring that the radar system remains effective even in constantly changing conditions. The rapid adaptability of these models makes them ideal for environments where interference is unpredictable and where quick responses are required. Moreover, ML-driven radar systems can make decisions faster than traditional statistical methods.

This enhanced decision-making speed is crucial in time-sensitive applications, such as security monitoring or navigation, where delays in processing could lead to safety risks or operational inefficiencies.

In summary, combining autonomous receivers, hybrid radar systems, and machine learning algorithms has significantly improved radar performance in various critical areas. These innovations have reduced false alarms, increased detection accuracy, and improved the system's ability to process signals in real time, even in complex environments. With these advancements, radar systems are becoming more reliable, efficient, and capable of handling the diverse challenges posed by modern-day applications.

While the proposed solutions offer significant improvements in radar system reliability, they also present several challenges that need to be addressed for optimal performance, particularly in real-time applications like air traffic control (ATC) and other mission-critical environments.

One of the main challenges is computational complexity. The integration of machine learning models and hybrid radar systems demands considerable processing power, especially when real-time performance is a requirement. To mitigate this issue, one effective strategy is to implement hardware acceleration. By utilizing specialized hardware such as Graphics Processing Units (GPUs) and dedicated signal processors, the computational burden can be significantly reduced. These accelerators are designed to handle parallel processing more efficiently, enabling the radar system to process data faster. This approach not only improves real-time performance but also ensures that the radar system remains responsive even as the complexity of tasks increases.

Another significant challenge is data availability, which is critical for training machine learning models. These models rely heavily on access to large, diverse, and high-quality datasets to effectively learn and make accurate predictions. However, acquiring such datasets can be difficult, particularly in the context of radar data, which is often sensitive and proprietary. Machine learning models require a variety of radar data to train effectively—this includes data from different weather conditions, terrains, and interference scenarios. Without access to comprehensive datasets, the models' performance could be compromised, particularly in dynamic and unpredictable environments. To address this challenge, collaboration with organizations like ATC (Air Traffic Control) agencies is essential. By working together, it may be possible to access anonymized radar data, ensuring that the privacy and security of sensitive information are maintained while still providing the data necessary for training machine learning models. This collaboration would also help ensure that the datasets used are relevant to real-world conditions, improving the accuracy and robustness of the models.

Finally, integration overhead presents a challenge when incorporating new technologies like autonomous receivers and hybrid radar systems into existing radar infrastructure. Upgrading or replacing traditional radar systems with advanced technologies can introduce operational disruptions, especially when the existing systems are already critical to ongoing operations. To mitigate these challenges, a phased implementation approach is recommended. This strategy involves gradually introducing new components into the system while conducting parallel testing to ensure that the new technologies do not disrupt existing operations. This method allows for the identification and resolution of any issues before full-scale deployment, ensuring a smoother transition and minimizing disruptions to critical operations.

The choice of hybrid radar architectures was based on their superior interference suppression capabilities, particularly in environments with high signal congestion. These architectures integrate both primary and secondary radar data, allowing for improved target differentiation and clutter rejection. Additionally, autonomous receivers were selected due to their ability to operate independently from traditional radar systems, enabling real-time detection of false alarms without requiring direct integration into existing infrastructure.

4. Conclusions

The findings outlined above demonstrate the effectiveness of hybrid radar systems, autonomous receivers, and machine learning techniques in mitigating interference and improving radar reliability. In this section, we further analyze the implications of these results, comparing them with existing literature and discussing their potential for large-scale implementation in ATC environments.

This study explored advanced methodologies to improve radar reliability in air traffic control (ATC) systems. By addressing critical challenges such as interference and clutter, the proposed solutions—autonomous receivers, hybrid radar systems, and machine learning applications—provide a roadmap for enhancing radar performance. Standalone receivers effectively isolate and suppress interference signals, reducing false alarm rates by 30% and enhancing signal clarity in real-time scenarios. By combining the strengths of primary and secondary radars, hybrid systems improve detection rates and positional accuracy, offering a robust approach to managing clutter in high-density environments. Adaptive and scalable, Machine Learning Models excel in signal classification and interference prediction, achieving high accuracy and operational efficiency.

The results of these developments highlight the substantial potential of the proposed solutions to enhance radar reliability, especially in ATC and other critical fields. While the solutions offer significant benefits in terms of improving detection accuracy, reducing false alarms, and enhancing system responsiveness, they also present challenges related to computational complexity, data availability, and integration. Addressing these challenges will require continued innovation, collaboration between industry stakeholders, and the careful implementation of strategies to ensure that the radar systems can scale effectively and integrate smoothly into existing infrastructures. With ongoing efforts to overcome these obstacles, the full operational potential of these technologies can be realized, ultimately leading to more reliable, efficient, and robust radar systems.

The findings of this study lay a solid foundation for further research and development in radar technologies for ATC systems.

Future research should focus on integrating modern technologies such as ADS-B and multi-position systems (multi-positioning) to enhance the capabilities of radar systems. Particular attention should be paid to the use of artificial intelligence for predictive analytics, which will improve forecasting and data processing. An important area is the optimization of machine learning models to ensure their operation in real time, including the use of hardware acceleration technologies. It is also necessary to develop scalable hybrid systems capable of efficiently managing high air traffic density at the global level.

Nomenclature

ACAS	: Airborne Collision Avoidance System
ADS-B	: Automatic Dependent Surveillance-Broadcast
ATC	: Air Traffic Control
CAA	: Civil Aviation Authority
CFAR	: Constant False Alarm Rate
DME	: Distance Measuring System
DSP	: Digital Signal Processing
GLONASS	: Global Navigation Satellite System
GPS	: Global Positioning System
MLAT	: Multilateration
RA	: Resolution Advisory
SAR	: Synthetic Aperture Radar
SNR	: Signal-to-Noise Ratio
SPI IR	: Surveillance Performance Interoperability Implementation Rule
SSR	: Secondary Surveillance Radar
STAP	: Spatio-Temporal Adaptive Processing
SVM	: Support Vector Machines
WAM	: Wide Area Multilateration

CRediT Author Statement

Teymur Aliyev: Methodology, Formal Analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Islam Isgandarov:** Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Supervision, Validation, Resources, Writing - Review & Editing, Project Administration, Funding Acquisition.

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