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Air Traffic Modernization and Control: ADS-B System Implementation Update 2022 – a Review

Automatic Dependent Surveillance–Broadcast (ADS–B) is a multiparameter surveillance system designed to improve key segments of air traffic: enabling real-time surveillance, raising safety and efficiency levels, and improving flight information and weather services. ADS-B consists of two subsystems, ADS-B Out and ADS-B In. Although only a complete system, ADS-B In/Out provides numerous benefits (additional situational awareness, more efficient oceanic routing, etc.) FAA and EASA only require ADS-B Out (by January and June 2020, respectively), whereby ADS-B In remains optional. Because of its many advantages, ADS-B In/Out will be popular, but there are some weaknesses, which are primarily related to its cyber vulnerabilities due to insufficient authentication and encryption in the applied protocol. In this paper, an overview of the ADS-B system is presented as an aid to understanding the security problems and the different ways of potential attack. In addition, this review deals with the current state of ADS-B deployment and its future perspective and challenges.

Keywords: Aviation, Air-traffic control, ADS-B, NextGen, Vulnerabilities, Cyber security

1. INTRODUCTION

Shortly after Lindbergh's flight over the Atlantic, aviation became a global industry. The key driver of civil aviation development is the need for fast transport of people and goods. Increased wealth and advanced accessibility have led to tremendous increases in air transport operations throughout recent decades [1], with the prediction that related to 2016, air passenger and air freight traffic is expected to double by 2034. Accelerated growth in the number of overflights finds the need to improve the use of airspace primarily in terms of economy and speed without compromising safety.

The expected number of flights will inevitably lead to more congested airspace and increased workload and stress level of the air traffic controllers and pilots who ensure safe, reliable, and efficient air travel. Therefore, it is necessary to provide new technical/technological solutions and equipment in all segments, both within the ground infrastructure and the aircraft, to perform better monitoring and data processing. Also, the mass use of Unmanned Aerial Vehicles (UAVs)/drones will further enlarge congestion of the near future sky, where millions of drones will co-exist with manned aircraft [2]. Besides technical/mechanical aspects, especially in the prototyping phase of UAVs/drone design and prototype manufacture in general [3, 4], there are significant cybersecurity challenges regarding these

unmanned aircraft, which fall outside the focus of this paper. In addition to the challenges related to surveillance and navigation in aviation, there are communication-related challenges. Good surveys on communication challenges and solutions in future aviation can be found, for example, in [5, 6].

With the aim to efficiently handle different issues related to airspace capacity, the Federal Aviation Admi–nistration (FAA) and European Organization for the Safety of Air Navigation (EUROCONTROL) are intro–ducing Next Generation Air Transportation System (NextGen) [7] and Single European Sky Air Traffic Management Research (SESAR) [8] programs in order to modernize Air Traffic Management (ATM) and imp–rove the sending/receiving of digital information. This represents the evolution of ground-based air traffic control into one based on satellite control systems with a number of communication links and services. In addition, to introduce uniform standards in aviation, In–ternational Civil Aviation Organization (ICAO) sup–ports implementing similar programs worldwide.

The need for modernizing the ATM launched two projects in 2004, funded by FAA NextGen and CASCADE. These projects should have forced the development of Automatic Dependent Surveillance-Broadcast (ADS–B), as a precise monitoring system, with the aim of reducing dependencies on costly and dated radar equipment [9]. It is envisaged that ADS-B has a special category 21 ASTERIX protocol for aircraft information exchange [10].

In 2010, the FAA published a final rule referred to US National Airspace, mandating all aircraft in certain classes to be equipped with ADS-B by January 1, 2020 [11]. With slight delays caused by the newly emerging SARS-CoV-2 virus-induced coronavirus disease

pandemic in 2019 (COVID-19), among other factors, the year 2022 marks the end of the timeline for imple–menting ADS-B system as a global standard in commercial aviation which represents a giant step in modernization and improving quality of aviation operations. What are the challenges of this moderni–zation? As FAA underlined [11], applying ADS–B does not cause any increased risk. As we know, ADS-B provides many benefits to both Air Traffic Control (ATC) and pilots, such as significantly improving flight crews' situational awareness, which enables pilots to make decisions with full awareness of the impact on other users and enables controllers to coordinate effici–ently as well as safe air traffic flow based on real-time aircraft information. Then, relative to traditional radar systems, ADS–B reduces deployment and maintenance costs while increasing the covered area significantly.

However, ADS-B has shortcomings due to a lack of integrity or authenticity in broadcast text messages. Hence, they can be interfered with by open-source software and communication equipment easily available on the market. Thus, the ADS–B system has a very simple "free to air" protocol vulnerable to different cyber-physical attacks [12-15]. Is open criticism and addressing the issue in this regard trivial, and what are the solutions? Are there ways to eliminate these threats? These questions opened up some new ones, may we be ready or not, ADS–B has arrived.

As we mentioned, the deadline for the imple–mentation of the ADS–B Out in the US was 2020. ADS–B In remains optional for a few practical reasons, such as implementation cost, equipment standards, and cockpit requirements. Given the benefits of applying the entire system ADS–B In/Out, pilots and controllers eagerly await its full implementation. The simultaneous application of ADS–B In with other systems should meet the following expectations [16]: ADS-B In should improve air traffic safety, efficiency, and capacity; The two system integration (ADS–B In and Trajectory-Based Operations, TBO) should give better mana–gement and control of a few high-density traffic opera–tions; ADS–B In integrated with TBO should improve the managing and control of a few high-density traffic operations; ADS–B In with Cockpit Display of Traffic Information (CDTI), CDTI Assisted Visual Separation (CAVS) and Interval Management (IM) instantly bring efficiency improvement and great benefits for the operators.

The ADS–B In system is intuitive and easy to follow with minimal pilot training. Namely, as pilots are familiar with the Aviation Communication Surveillance Systems (ACSS) and the Traffic Collision Avoidance System (TCAS), internationally known as ACAS displays, it's a very simple transition to new ADS–B In displays. Behind all of this, there are still ADS–B security vulnerabilities. Therefore, there is a prompt necessity for improving ADS-B security.

Today, two years after the mandate regulation enters into force, why is ADS–B still a topic, have any problems been identified, and what are the latest challenges and opportunities? What should we expect, and does the ADS-B provide post-mandate airline benefits? As end users, are the pilots and air traffic

controllers involved and educated enough about all aspects of the ADS–B system operating, and are they especially familiar with possible malfunction or spoofing threats and countermeasures? To get started and get at least some answers, understanding this novel technology is necessary. Basics of ADS–B (infrastructure, operation, and limitation) are given in the following, as an aid to understanding the security problems and the protocol constraints, as well as to perceiving the different ways in which ADS–B may potentially be attacked and consequently jeopardize the aviation safety in all its aspects. As ADS–B equipment can have different pilot interfaces (from simple to control interfaces with advanced features), some aspects of the relationship between ADS–B and the human factor are also discussed. Besides, in the current review, we briefly deal with some challenges in ADS–B deployment and the future direction of ADS–B development in the context of a framework for an advance modernized aviation system.

ADS–B basics

ADS–B is a dependent and cooperative surveillance system in which an ADS–B transponder is placed in the aircraft that uses satellite navigation technology (Global Positioning System, GPS, and Global Navigation Satellite System, GNSS) for periodically exchanging (transmit and receive) important information with ATC centers and other neighbor aircraft. So, ADS–B is an acronym that denotes the essence of the protocol operates. It means that the ADS–B system: is Automatic (periodic information transmission without any control of the pilot or operator) and Dependent (information transmission with regards to the position and velocity vector that is obtained from the GPS/Flight Mana–gement System (FMS) and navigation avionics), and provides: Surveillance (it assures a method for deter–mining the three-dimensional position and identification of aircraft, vehicles, or other assets) and Broadcast (it transmits information such as identity, position, velocity, etc. available to anyone with the appropriate receiving equipment.

ADS-B system: infrastructure and operations

The three main components of the ADS–B system is [17-20]: ground infrastructure (Ground Based Transceiver stations and antenna system), aircraft equipment (ADS-B Avionics, GPS/GNSS, CDTI, FMS, etc.), and operational procedures (ADS-B regulatory basis for the implementation and use).According to the direction of aircraft information transmission, ADS–B can operate as ADS–B In and ADS–B Out. The former feature enables the frequent broadcast of accurate aircraft position and vector data together with other information, while the latter feature enables the display of real-time ADS–B tracks on a situation display in the aircraft cockpit. ADS–B Out operates independently and provides air-ground surveillance services by periodically sending the position and other information to controllers or neighbor aircraft.
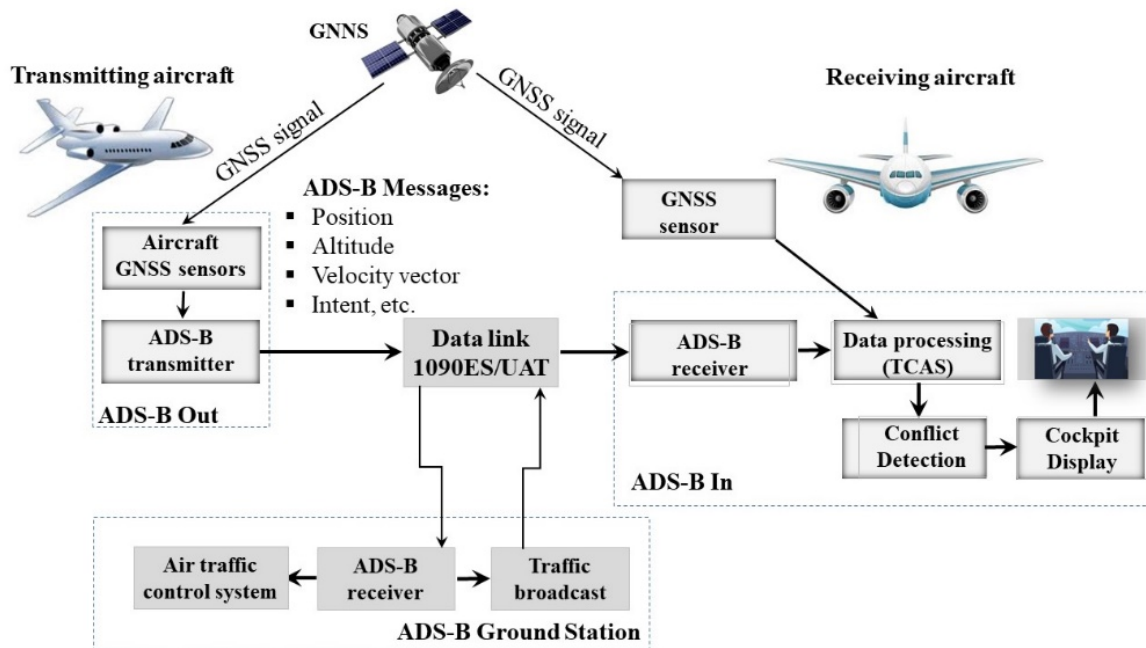
Figure 1. ADS–B system architecture: ADS-B Out, ADS-B In, Datalink, and Ground Station (adapted and modified from [19])

Thus, unlike current transponders, these broadcast ADS-B messages are sent periodically without being inter–rogated. Both ground-based and air-based receivers simultaneously receive these messages. Data obtained from these messages use other aircraft and their own parameters to create a three-dimensional state vector for calculating relative range and bearing. Key prerequisites for fully implementing ADS-B In are a cockpit display certification and considering human factors.

As depicted in Fig. 1, the ADS−B system comprises Ground Stations, ADS−B Out, ADS−B In, and dual-band data links [18]. An aircraft equipped with ADS-B using GNSS sensors retrieves its position obtained by using a reliable position source. ADS-B Out periodically transmits aircraft position, velocity, and trajectory intent data in a message format 1090 MHz Extended Squitter/Universal Access Transceiver (1090ES/UAT) to the other aircraft and ground stations that are equipped with these systems. For fully processing and exchanging ADS-B messages, ATC ground stations, and neighbor aircraft must be equipped with ADS- B In. Each aircraft can have "In" and "Out" capabilities, depending on which option is installed ADS-B Out sends messages every second at a bit rate of 1 Mbit/s over 1090-ES or UAT [9]. Communication within the ADS-B is realized by standardized communication protocols such as 1090ES/UAT, 987 MHz UAT, and VHF Datalink Mode 4 (VDL-M4), depending on aircraft type. ADS-B has an open-access protocol (good interoperability), but its messages have an unsatisfactory encryption level: the last 24 bits include a parity check that detects and corrects transmission errors in the messages. For more details on ADS-B message format, see [11, 21-23].

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2. ADS-B APPLICATIONS: STATE-OF-ART AND FUTURE

As the backbone of modern ATC, the ADS-B will increase safety by adding an extra layer of surveillance and inter-communicative capabilities between aircraft and ATC. This reduces the separation between aircraft and the risk of collision as air traffic density increases, enlarges spatial awareness, and abates the fuel cost. At the same time, ADS-B contributes to improving the quality of the environment by reducing emissions and noise [17-26]. Based on these ADS-B advantages, more and more applications are being derived, especially in surveillance systems with air-to-air and air-to-ground applications.

ADS-B applications can be classified into groups [17], for example, in data link, ADS-B Out, and ADS-B In applications [27]. Up to now, the standardization has to be done for all ADS-B Out, as well as Airborne Traffic Situation Awareness (ATSAW) applications, and delivers the safety, performance, and interopera–bility requirements for different ADS-B applications such as ADS-B in Non-Radar Airspace, ATSAW In-Trail Procedure in oceanic airspace, ATSAW Visual Separation in Approach, ATSAW on the Airport Surface, etc.

Nowadays, SESAR, NextGen, European Organi–zation for Civil Aviation Equipment (EUROCAE), and Radio Technical Commission for Aeronautics (RTCA) are rapidly planning the current and future stan–dardization activities that should cover spacing, sepa–ration, and self-separation applications.

ATC's new ADS-B real-time precision tools are now the preferred surveillance method that helps controllers. This method facilitates the management and raises air traffic's reliability, safety, and capacity [28]. The information of ADS-B aircraft tracking is fast transmitted to controllers and pilots for shared situational awareness, while aircraft-to-aircraft ADS-B transmission enables ATC advantages for allowing aircraft to maintain precise time intervals and space distances. These services are provided through Wide Area Multilateration (WAM), Airport Surface Surveillance Capability (ASSC), and Advanced Surveillance Enhanced Procedural Separation (ASEPS). WAM is a ground-based surveillance system that offers surveillance outside the range of radar coverage and enhances efficiency, safety, and capacity by reducing flight delays, diversions, cancellations, and fuel emissions. ASSC helps prevent runway collisions leading to fewer surface delays. ASEPS, as the subsequent level of NextGen, provides safety and efficiency benefits in oceanic Flight Information Regions.

In the cockpit, ADS-B pilot applications [28] assure a higher safety and efficiency level and better information. ADS-B offers broadcast services for Traffic Information Service-Broadcast (TIS-B) and Flight Information Service-Broadcast (FIS-B). TIS-B increases the pilot's situational awareness by broadcasting accurate real-time traffic position reports, which are relevant to the properly equipped aircraft. FIS-B is available only to those aircraft that can receive data over 978 MHz (UAT). It broadcasts real-time aeronautical and weather information (turbulence, lightning, icing, etc.), which aids the pilots in efficiently planning a safe flight path, and during the flight, it helps them to make strategic decisions to avoid hazardous weather conditions. For instance, the pilot application can use flight and weather information received (via ADS-B In receiver) from UAT broadcasts.

An ADS-B based ADS-B Traffic Advisory System (ATAS) is useful for monitoring possible traffic conflicts and for audible and/or visual warnings. This inexpensive alerting capability for general aviation reduces the air collisions risk potential [28]. Then, IM is the ADS-B in the flight-deck application, used by flight crews and air traffic controllers to more efficiently and precisely manage space between close aircraft. In addition, as previously mentioned in IM, ADS-B increases crew awareness by giving timely recommendations for speed adjusting, which aids the crew in keeping necessary spacing from other aircraft. In addition to providing consistent, low-variance spacing between aircraft leading to increases in arrival throughput and maintaining efficient flight paths during high-density traffic periods, the benefits of using IM are also reducing fuel consumption, noise, and emissions. Besides collaborating with American Airlines and ASSC to certify and install ADS-B In avionics on American Airline's entire fleet of Airbus A321 aircraft starting in 2022, the FAA is developing automation requirements and plans to deploy IM operations throughout the whole US National Airspace System (NAS) after 2024 [28].

Today, two applications In-Trail Procedures (ITP) and CAVS, are utilized [28, 29]. ITP application (only for ITP−equipped aircraft) is responsible for ideal flight levels, emission−reducing, and decreasing fuel costs [17-24, 27, 28]. CAVS is an Airborne Surveillance Application to assist the flight crew in better maintaining their separation from a preceding aircraft during a successive visual approach procedure. The data of the preceding aircraft (derived from ADS-B Out) and received by the succeeding aircraft (via ADS-B In) are presented to the crew on a cockpit display (CDTI). Thus, CAVS improves pilot situational awareness due to visual display of traffic and reduction of possible go-around procedures. CAVS is expected to gather data on the ADS-B In flight-deck equipage benefits with commencing operations over two years (2021-2022). As aircraft are equipped with ADS-B In avionics, more applications will improve safety, increase capacity, and reduce harmful aircraft emissions. In all of this, as Don Van Dyke emphasized: "Modernization of global airspace requires cockpits to meet operational demands with innovative technology that accommodates human factors to unprecedented levels" [30].

Analyzing safety-related issues has become very important concerning the interaction of humans with automated onboard systems that have become increasingly complex in recent years [31]. Implementing new equipment and procedures in the ADS-B will increase human factor issues such as understanding the use of equipment (controllers operation and CDTI), entry and readability of the data, and other human factors. As mentioned, ADS-B data will provide data from which many applications may derive. Those will be very helpful for different uses, such as examining pilot performance with an ADS-B based Traffic Situation Awareness with Alerting Application (TSAA) system for general aviation [32].

Pilots, controllers, and dispatchers are among those users who find using ADS-B technology crucial and need clear information within their relevant responsibilities. As pointed out [17], it is upon certificated authorities and the rulemaking team to delegate the roles and responsibilities of pilots and controllers in such a fashion that will contribute to overall safety. Besides, the next challenge would be to develop an ATM system that integrates the human factor so that the entire system functions efficiently.

3. ADS-B SYSTEM: ADVANTAGE, LIMITATIONS, AND SECURITY

Security, efficiency, and capacity are not the only benefits that ADS-B presents. It improved accuracy, integrity, and reliability via satellite-based information. ADS-B will enable more aircraft to navigate increasingly crowded airspace without sacrificing safety. Aircraft can also take more direct flight patterns, saving time and fuel and reducing emissions. Pilots will see the same visuals available to air traffic controllers (other aircraft, weather, and hazards in their flight area and on the ground), which increases safety during take-offs, landings, and in-flight. Additionally, it expands the

satellite-based information to areas previously not served by radar.

The main limitations of ADS-B are related to radio frequency (RF) communications, as the transmitted messages are in text form, which is not encrypted and without any authentication. That makes them the target of authorized/unauthorized individuals (hackers) that can have malicious intents and may hack ADS-B messages that can have delicate information when eavesdropped on and discontinued [13, 35]. But, there is some drawback, such as the system dependency on the positioning system accuracy, i.e., GNSS, which can be subject to jamming and spoofing that could corrupt, damage, or interfere with the positioning information [33, 34].

Due to these limitations, different cyber-attacks on the ADS-B system are possible [34]. Researchers have already underlined various attacks that can be executed with the help of simple components (Commercial-Off-The-Shelf software, COTS) and fundamental knowledge [15] and consequently classified them into different categories. Message insertion (spoofing), jamming, eavesdropping, and deletion and modification of messages [13, 22, 34-43] are just some to point out. Aircraft systems can be subject to these attacks on various levels, from minimal, as in the case of eavesdropping, to great one, as in the case of spoofing by fake/false messages. This can lead to a situation where the receiver believes it is at a different location. In the attack named "boiled frog" (spoofing), the method operation of the attacker is small, but continuous changes in the position of the aircraft are made through the ADS-B protocol [42], as it is difficult to detect differences if they are small and within adjustment accuracy, for surveillance technologies. This can lead to ATC control of aircraft that is not accurate, as well as the delayed response of the system regarding mid-air collision prevention. Another weakness that has been highlighted is the introduction of a "ghost–plane" by means of a mimic of the ADS-B signal, which can easily be achieved by using software and devices that are considered low-cost technology [15]. This form of message modification is considered a typical spoofing attack, and the ATC system is greatly impacted by it. It should be emphasized that, unlike spoofing attacks from the ground, potential attacks that could be carried out from the air (the attacker is in the air) are still insufficiently investigated[15], but they represent a real threat. These attacks can be realized using drones, i.e., UAVs (unmanned aerial vehicles), and special attention must be paid to this type of potential attack. Because of all this, the OpenSky Network research project collects ADS-B reports and makes them available for security /safety analysis and development of spoofing attack detection concepts and locating spoofing devices/sources.

Regarding the protection of wireless ADS-B communication, mechanisms and countermeasures should be incorporated, which would test the integrity and trustworthiness of the messages received. Over the past decade, in many research papers securing broadcast protocols in wireless sensor networks has been a very important issue. Various researchers have taken part in the security research of ADS-B systems to recommend solutions to enlarge ADS-B security. Numerous security mechanisms are proposed, and the solutions can be categorized as secure location verification and broadcast authentication solutions. However, a detailed analysis of the ADS-B attack, countermeasures, their advantages/disadvantages, and implementation issues and problems can be found in recently published review papers [13, 38, 44]. Shortly, we can divide secure broadcast authentication solutions into non-cryptographic and cryptographic schemes on the physical layer. Crypto–graphic techniques for the authentication of messages consist of symmetric and asymmetric mechanisms (public key crypto, PKI, Timed Efficient Stream Loss tolerant Authentication, TESLA, and Message Authentification Crypto). Still, those require existing ADS-B modifications of protocol/overheads that move the problems to secure designing and modular schemes for distribution and management. Consequently, they are difficult to implement [45, 46].

On the other hand, non–cryptographic techniques pass around the key distribution problem, incorporate physical–layer fingerprinting approaches, and spread spectrum technology. Another securing approach to ADS-B communications is secure location verification solutions which, unlike secure broadcast authentication, strive to identify and verify the locations declared by entities of the ADS-B network [38]. These solutions include different techniques [13] such as distance bounding, Kalman filtering, multilateration (MLAT), and data fusion. In recent years various techniques build on models of machine learning [47], Long Short–Term Memory (LSTM) networks [22], SODA-DNN (Deep Neural Network) [43], MAVPro[48], etc., also have been proposed.

Please, see the survey in [38, 44] for details.

The following question is whether some of these approaches provide the ADS-B comprehensive security framework. The proposed security solutions/methods efficacy relate to the sophistication level of the false signals generating device, i.e., attack scenarios. The comprehensive overviews of the published papers on the latest ADS-B security solutions show that even though every solution gives a certain security level, more than a single detection/defense solution may be required to secure ADS-B communications [13, 38, 44]. Therefore, a necessity exists for a multi–layered secu–rity framework to be proposed, which would include a variety of plain methods that can detect and mitigate different ADS–B attacks. In the future, the principle research challenge would be to manage and control security layers; for ADS-B security verification, deep learning methods may be a potential solution, such as DNN, to analyze vulnerabilities combined with blockchain technology [49]. On the other hand, although some new technical/technological solutions have increased the security of infor–mation and network, as well as threat detection, it is obvious that human decisions built on past knowledge [50], as well as skills, are necessary to address critical situations [51].

4. ADS-B: CURRENT STATE IN DEPLOYMENT AND CHALLENGES

Modernization programs of projects such are EUROCONTROL's SESAR (Single European Sky

ATM Research), and FFA's NextGen (Next Generation Air Traffic Management) have the key enabler in common, that is ADS-B, with the goal of enhancing airspace capacity and ensuring safety short of the threatening environment [11].

Certainly, the year 2020 will remain remembered as a turning point in aviation history in view of not only the FAA and European Union Aviation Safety Agency (EASA) issued ADS-B mandate. The newly emerging SARS-CoV-2 virus-induced coronavirus disease pan–demic in 2019 (COVID-19) struck a drastic blast on aviation generally, i.e., slashing passenger traffic glo–bally [52], immobilized many aircraft, as fleet mana–gement plans were significantly changed in a way that order was canceled and also aircraft met early reti–rements. The analysis of the effects of the Covid19 outbreak, such as environmental and enviro economic impact on commercial flights [53] and human factor impact on the maintenance of air safety [54], as well as an overview of the present situation in air traffic globally with updates of equipment, ADS-B application, fleet management by airlines and so on, by using broad air traffic dataset originated from the full OpenSky data, can be found in more recently published manuscripts [52, 55, 56].

Through the mandate known as SPI IR, the European Commission requires aircraft operators to equip them with particular surveillance functions. The goal is to transform European surveillance infrastructure into more powerful ADS-B technology with substations reducing costs. SESAR Deployment Manager, starting from December 2018, continuously updates the plan annually. According to SESAR, the present percentage implementation of ADS-B equipage, more precisely ADS-B version 3, is 87.6% (August 2021), and comprised aircraft that are subject to the SPI IR mandate as well as registered in EU27+4 (Fig. 2) [57]. Various ADS-B mandates are already in place or anticipated worldwide. From the global mandate map [57], and whenever new information is available, the map is updated and maintained, shows the regions with different requirements (at least ADS–B version 0 for Australia, Mongolia, India, Vietnam, Indonesia, Malaysia, and Papua New Guinea, and ADS-B version 2 for the USA, EU, South Africa, Mexico, Colombia, and New Zealand). Also displayed are anticipated dates of coming into effect, as well as regions with ongoing regulatory activity and mandates that are supposed to happen in the near future (Canada, China, and Saudi Arabia).

In the future of aviation, an increasing number of aircraft in the airspace will result in overcrowding, and thus the number of ADS-B messages will rise, too. Consequently, there are many challenges in the ADS-B prospect advancement, such as avoiding channel congestion and message loss on the 1090 frequency band, i.e., providing efficiency, which would be realized by fast and accurately receiving and processing ADS-B messages. One of the future development trends is the space-based ADS-B, a relatively recent technology based on the use of a matrix of satellites in order to supply ADS-B coverage "from above". Thus, the world's very first licensed provider of the service for

oceanic separation of aircraft is Aireon (certified by May 2019 from EASA as a new Air Navigation Service Provider, ANSP). Soon after, EUROCONTROL and Aireon inscribed an arrangement related to using space-based ADS-B data in order to boost the management of air traffic flow in Europe.
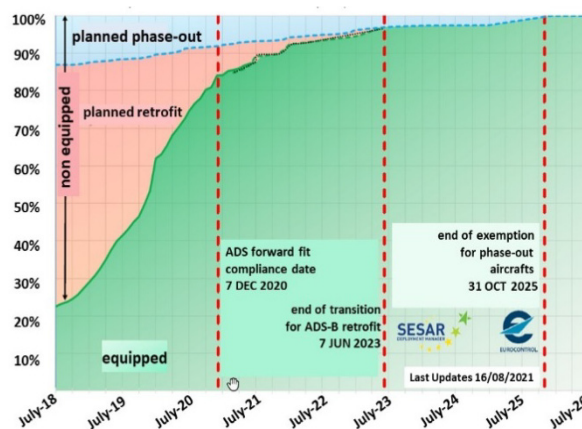

Figure 2. Evolution of the ADS-B equipage (EU27+4): planned fitments (dot line), planned phase-out (dash line), and detected (solid line), according to SESAR [59]

Now that the ADS-B Out mandate became a regulation, certain problems have emerged, such as the Flight ID issue (Call Sign Mismatch, CSMM). This will be a problem for FAA, and airspace users over all segments as new ADS-B In applications such as IM are increasingly used [58]. As the FAA explained, essential causes of CSMMs are the ADS-B transceiver's incorrectly programmed Flight ID field throughout installation, unusual call signs, and CSMMs, which occur when an aircraft undergoes maintenance. Besides CSMMs, other errors, such as NPE (Non-Performing Emitter), occur. This refers to a situation when aircraft, although properly ADS-B Out equipped, thus do not transmit in an orderly manner and do not comply with FAR 91.227 requirements. However, the agency is currently working with operators to eliminate pilot/crew-related errors such as CSMMs and NPE.

The ADS-B provides post-mandate airline benefits. One of the considerable improvements is the enlarge-mentation of supervision to airports and areas where the FAA did not previously have significant radar coverage. Then, the most flight operational advantages of the space-based ADS-B system show great potential in oceanic regions, as this system can advance the fore-casting of short-term aircraft trajectories. In addition, numerous experts consider that the later strides for ADS-B related to providing flight operational conveni-ences for airlines will be gained from using ADS-B In on accordingly equipped displays. The latest upgrade for ADS-B by the RTCA Special Committee 186 incorporates publishing the Minimum Operational Performance Standards (MOPS) for 1090ES ADS-B Version 3.

This ADS-B Version expands the available information spectrum, from monitoring, across weather information to airspeed, improves weather forecasting, makes wake turbulence application possible, and improves other ADS-B In applications such as IM.

#	Time	Latitude	Longitude	Heading (°)	Altitude (ft)	Ground speed (kts)	Vertical speed (ft/min)	Source	SQUAWK
1	05:16:46 UTC	25.0929	102.9101	↙ 221	8225	178	↗ 2560	ADS-B	
2	05:17:46 UTC	25.0542	102.8599	↙ 232	9350	249	↗ 896	ADS-B	2101
3	05:18:46 UTC	25.0056	102.8072	↙ 197	12325	259	↗ 3712	ADS-B	2101
4	05:19:46 UTC	24.9404	102.8548	↘ 146	14475	346	↗ 2560	ADS-B	2101
5	05:20:46 UTC	24.8978	102.9512	↘ 116	17325	353	↗ 2752	ADS-B	2101
6	05:21:46 UTC	24.8525	103.0513	↘ 115	19025	382	↗ 2880	ADS-B	2101
7	05:22:46 UTC	24.7962	103.1513	↘ 141	21050	384	↗ 1472	ADS-B	2101
8	05:23:46 UTC	24.6983	103.1967	↘ 158	22950	396	↗ 2240	ADS-B	2101
9	05:24:46 UTC	24.6055	103.2646	↘ 134	24800	418	↗ 1856	ADS-B	2101
10	06:00:46 UTC	23.7387	108.1344	→ 093	29100	461		ADS-B	2101
11	06:02:48 UTC	23.7227	108.4190	→ 093	29100	461	64	ADS-B	2101
12	06:05:45 UTC	23.6998	108.8146	→ 093	29100	458	64	ADS-B	2101
13	06:17:45 UTC	23.4143	110.4491	↘ 100	29100	454		ADS-B	2101
14	06:19:45 UTC	23.3702	110.7202	↘ 100	29100	457		ADS-B	2101
15	06:20:45 UTC	23.3479	110.8558	↘ 100	29100	457		ADS-B	2101
16	06:21:45 UTC	23.3149	110.9834	↗ 081	7850	590	↘ −15744	ADS-B	2101
17	06:22:36 UTC	23.3375	111.1056	↗ 087	3225	376	↘ −32640	ADS-B	2101

Figure 3. China Eastern Airlines flight MU5735 operated by Boeing 737-800: reported ADS–B messages, covering the time period from 05:16:46 to 06:22:36 UTC according to AirNavRadarBox [61]

According to the research and experience feedback of pilots as end users, this new technology was presented to them through numerous Electronic Flight Bag IPad platforms. Further continuous equipping of the fleet encourages pilots to be acquainted with new tools and smoothly conduct CAVS during their flights. The experience gained is very important, considering that other applications, such as IM, are demonstrated and applied [59]. Namely, the aircraft pilots occupied with ADS-B In enter certain information obtained from an air traffic controller (for example, the spacing goal, the trajectory the aircraft should fly, and the ID of an aircraft ahead of them) into FIM (Flight-deck Interval Management) system. Then, the FIM system calculates a solution with the additional assistance of input from the airplane's ADS–B unit. As a result, the FIM screen displays the values of the optimal flight speed that allows a safe distance of a given aircraft from others in front of it, all the way down to the runway. This application allows the pilot to better control the distance of his aircraft compared to other aircraft equipped with ADS–B, which is especially important at busy airports.

In the end, as pointed out [7], leveraging the NextGen infrastructure will also enable implementing TBO, as well as lead the way to accommodate all operations (procedures for full integration of UAS/drones, space launch, and re-entry operations, continuing research aimed to reduce aviation's environmental footprint and increase cybersecurity, etc.). In addition, as the infrastructure transforms, the FAA will introduce additional changes. For example, data communications are enlarging to en route flight– initial Data Communications En Route Services gives pilots and controller's ability to interchange messages like reroutes acknowledgments, communications transfer, and also initial check-in, while complete services will diversify counting digital information interchange to holding instructions as well as advisory messages.

In addition, Performance Based Navigation (PBN) coverage increases with Distance Measuring Equipment (DME) area navigation. ADS-B continues to offer more operational benefits such as ADS-B In applications, detection of conflict and searching/rescuing. The contribution to the latter, based on ADS-B data, has already proven to be very significant, unfortunately, among others, in the most recent event of China Eastern Airlines Boeing 737-800 (registered B-1791) carrying 132 passengers crash on March 21, 2022, into the mountains of south China's Guangxi Province. Although not the only tool helping to locate crash sites, from the ADS-B data omitted from the aircraft, the final trajectory can be more easily reconstructed. Based on this accident, we can see more fully the broad possibilities of what the ADS-B system allows. Namely, FlightRadar24 collected ADS-B data [60], streamed directly from the aircraft's computers during its flight. More precisely, the last reported ADS-B message provided by AirNavRadarBox data [61] was at 06:22:36 (UTC), and a vertical speed of −32,640 ft/min indicated that the aircraft plummeted (Fig. 3). Also, it should be emphasized that these ADS-B data, longitude and latitude could be observed so that descent trajectory could be reconstructed, and the crash site more precisely identified.
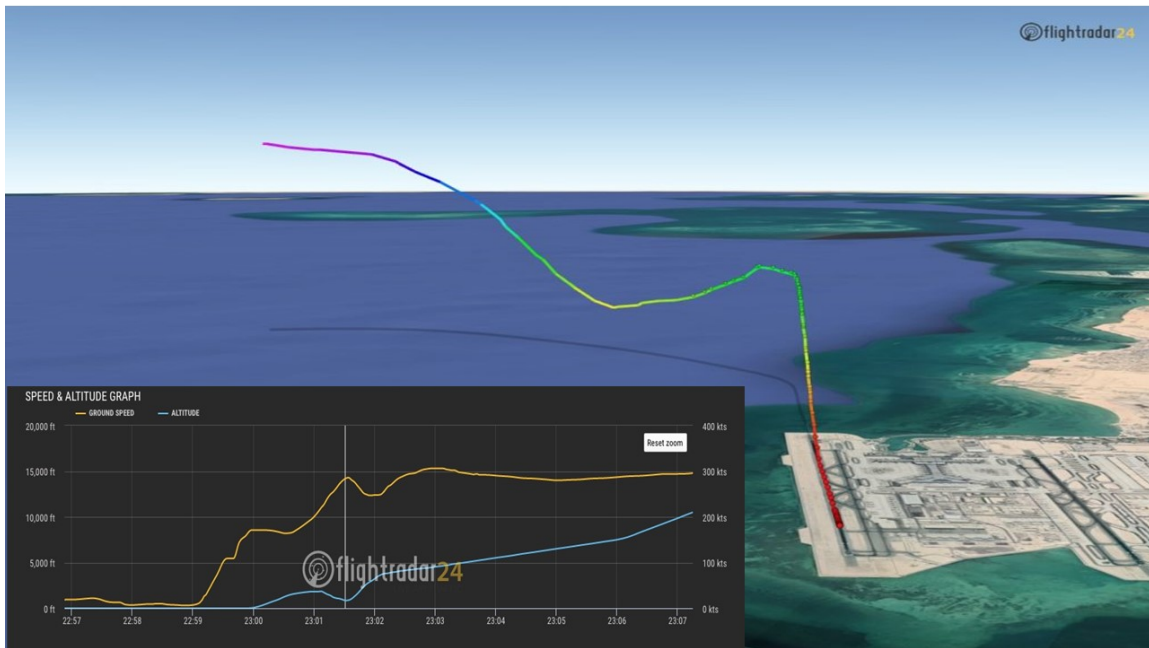
Figure 4. Map and flight trajectory of Qatar Airways flight QR161 (January 10, 2023) based on ADS-B data. Insert: ground speed and altitude graphs [64]
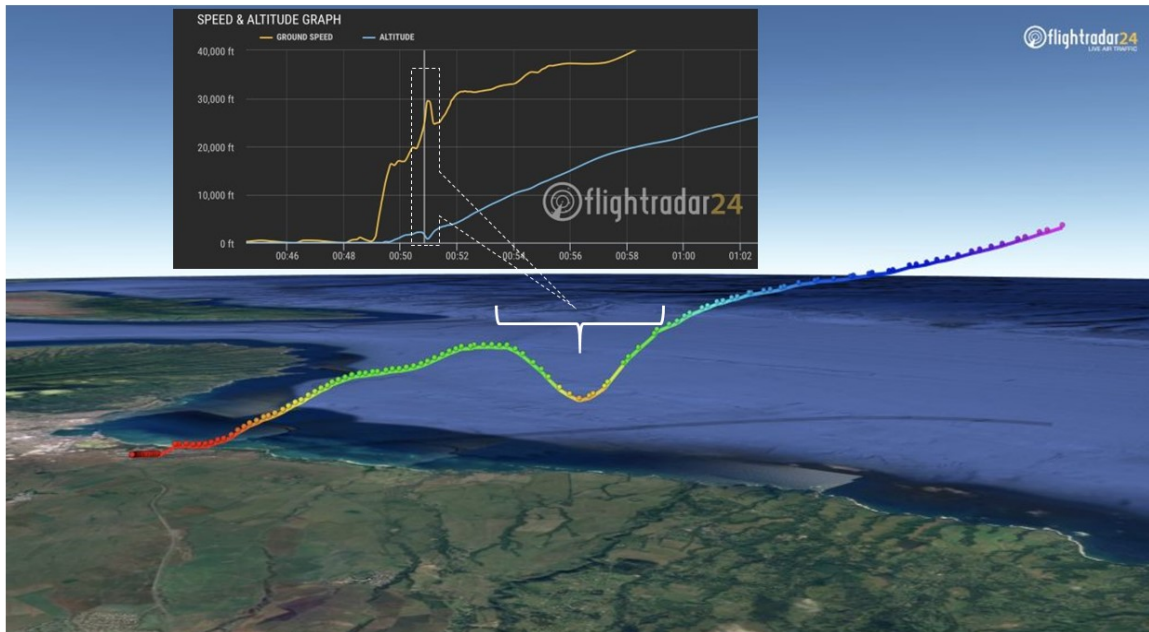

Figure 5. Map and flight trajectory of United Airlines flight UA1722 (December 18, 2022) based on ADS-B data. Insert: ground speed and altitude graphs [69]

Aircraft accident investigators are methodically and systematically reviewing evidence and considering all potential factors to determine the probable accident cause. ADS-B data show details of aircraft incident situations. For example, the Learjet was involved in a fatal accident (December, 2021) at Gillespie Field in El Cajon, California [62]. As derived from ADS-B, the aircraft showed an unstabilized approach as the pilot attempted to circle for landing, according to the preliminary report from the National Transportation Safety Board (NTSB). Further, according to ADS-B data and relevant position information, the NTSB preliminary report related to the fatal mid-air collision between a B-17G and a P-63F Kingcobra (registered to the American Airpower Heritage Flying Museum) during the Wings Over Dallas air show (November, 2022), showed that there were no altitude deconfliction's briefed [63]. The weather at the time of the accident, in which 6 people lost their lives, was reported as clear skies, and the winds were from 350° 14 knots with gusts up to 18 knots. Both aircraft were equipped with ADS-B and GPS. In addition, the B-17G had an Avidyne IFD540 unit, and investigators noted the GPSMap 496 from the fighter did not record any information for the accident flight. The final report is yet to be released. Also, the most recent incident of Qatar Airways Boeing 787-8 (registration A7-BCO) from Doha to Copenhagen (January, 2023), which had steep descent after take-off the aircraft climbed to about 1800 feet when it entered a steep descent losing 1000 feet within 24 seconds [64]. The aircraft recovered, climbed out, and continued to Copenhagen, where it landed safely about 6 hours later (Fig. 4).

Table 1. United Airlines flight UA1722 operated by Boeing 777-200ER: reported ADS-B messages, covering time period from 00:50:37:759 to 00:51:11:250 UTC according to the Air Current [69]

Timestamp	Latitude	Longitude	Altitude (ft AMSL)	Grounds speed (Kts)	Track	Vertical rate (fpm)	Receiver	GPS Alt (ft)
00:50:37Z.759	20.94413	−156.402	2175	203	30	576	1521	GPSA:2150
00:50:39Z.007	20.94478	−156.401	2200	208	30	192	40218	GPSA:2175
00:50:40Z.389	20.9464	−156.4	2200	210	30	−64	1521	GPSA:2175
00:50:42Z.005	20.94786	−156.399	2200	216	31	−384	40218	GPSA:2175
00:50:43Z.775	20.94919	−156.399	2175	222	31	−1216	1521	GPSA:2125
00:50:45Z.029	20.95051	−156.398	2175	227	31	−2112	40218	GPSA:2100
00:50:46Z.659	20.952	−156.397	2075	230	31	−4224	1521	GPSA:2075
00:50:48Z.084	20.9533	−156.396	1950	238	31	−5888	40218	GPSA:1925
00:50:49Z.965	20.95516	−156.395	1725	246	31	−7168	1521	GPSA:1675
00:50:51Z.409	20.95661	−156.394	1550	252	31	−8192	40218	GPSA:1575
00:50:52Z.640	20.95789	−156.393	1350	259	30	−8576	1521	GPSA:1400
00:50:54Z.499	20.95996	−156.392	1075	273	29	−7680	40218	GPSA:1050
00:50:55Z.965	20.96191	−156.391	900	287	28	−5184	1521	GPSA:900
00:50:57Z.500	20.96373	−156.389	775	295	28	−2304	40218	GPSA:825
00:50:59Z.170	20.96568	−156.388	825	300	28	2816	1521	GPSA:825
00:51:00Z.197	20.9664	−156.388	875	300	28	3712	40218	GPSA:875
00:51:01Z.680	20.96862	−156.387	1050	294	29	7168	40218	GPSA:1025
00:51:02Z.245	20.96919	−156.386	1150	286	29	7744	1521	GPSA:1150
00:51:05Z.237	20.9722	−156.384	1625	256	30	8640	1521	GPSA:1575
00:51:06Z.245	20.97318	-156.384	1775	247	29	8128	40218	GPSA:1700
00:51:08Z.196	20.9751	−156.383	2000	248	29	7168	1521	GPSA:1925
00:51:11Z.250	20.97821	−156.381	2350	247	30	5760	1521	GPSA:2275

Related to all this, as known, the flight path is affected by atmospheric/weather conditions, aircraft asymmetry, engine failure in multi-engine aircraft, asymmetrically placed cargo, and sudden damage during flight (bird strike, hail, etc.). Thus, it is very significant to determine the boundaries of the safe flight envelope based on the comparison between the available and demanded deflection of the control surfaces, that is, on the limiting authority of flight controls. The method based on these demanded flight control displacements (related to the maneuvering requirements and those needed to compensate for lateral wind and any asymmetric airplane load), combined with numerical simulations, is proposed [65-68]. In addition, this relatively simple and robust method applies to the analysis of the cases of asymmetric loads of the airplane in both regular use and failure states.

One recent example [69] of flight path deviation possibly due to weather conditions is the United Airlines flight (UA1722), Kahului to San Francisco (December, 2022). The flight departed normally, but 71 seconds after take off, the aircraft entered a steep dive and descended from 2200 feet to just 775 feet before recovering and continuing its flight (Fig. 5). Deviation was broadcasted and could be analyzed by ADS–B data. The ADS-B data provided by Flightradar24 (granular CSV file that includes high-frequency data for departure only) is given in Table 1. Particularly, the data set shown in table 1 is related to the phase of flight in which the aircraft reached about 2200 feet, then entered a descent reaching 775 feet, and then began to climb again (a curly bracket indicates the flight trajectory part in Fig. 5).

From ADS-B data one can obtain quantitative infor–mation that is inherently related to airplane dynamics and, therefore, can be used to compare with dynamic model predictions. That is, the ADS-B allows fine-tuning para–meters that make it possible to trace aircraft trajectory sequence, which corresponds to certain phases of flight.

Modern methods based on powerful artificial intelligence (AI) models have been designed to solve various complex problems in practice [70]. Thus, with the exponentially increasing amount of data for analysis (for example, ADS-B data), various and increasingly sophisticated machine learning algorithms may be designed that enable, for example, handling of aerodynamic environments possibly exhibited in abnormal (nonlinear and unsteady) flight condition, particularly in hazardous weather (in-flight icing, wind shear, atmospheric turbulence, etc.,) [71, 72]. In the end, it should be emphasized that such approaches based on these large amounts of air traffic data can be useful in a wide range of air traffic management investigations that rely on operational data and statistics [73].

5. CONCLUSION

January 1, 2020, flagged a landmark in history for the aeronautics community. Within this, the ADS-B In stands as an option, as worries over systems cost of implementation, equipment performance standards, and cockpit display requirements. But, ADS-B In appli–cations built on ADS-B Out, such as ATAS, advanced IM, and ITP, offers many leverages. The operator would benefit with no extra cost in receiving flight, traffic, and weather info services, providing that the aircraft is equipped with the system. In addition, the satellite-based ADS-B marks the direction for future progress and evolution, which will produce superior surveillance and enhanced system security, with additional systems that can also be facilitated.

As a new technology, ADS-B brings numerous advantages, improving and enhancing situational awareness, detection of possible conflict, and routing efficiency. Surveillance coverage is also extended, and operational costs are reduced. Security, efficiency, and capacity are put to a higher level. Although the functioning ADS-B is crucial, robust/powerful mechanisms for security are not incorporated. Commercial air traffic airports using the ADS-B system do not designate mechanisms to guarantee the authenticity of the trust protocol messages; furthermore, they are not replaced or cling to security properties. It is yet to be shown beyond doubt for most of the proposed technological mitigation solutions efficiency, as they could bring significant advantages, once they are out of the experimental stage. Besides, an all-inclusive defense system is non-existing. Current solutions cover only some portion of the diversity of the type of attacks. So, continuous surveys of existing solutions' theoretical and practical applications are necessary. In shielding against a variety of ADS-B assaults, there should be a multi-level security framework proposed. This security plan should be entrenched in deep learning methods combined with new technologies like blockchain to test vulnerabilities.

In addition to the FAA working on eliminating some problems, such as the Flight ID issue, the agency is working on putting it into operation NextGen. The long-standing objective of NextGen is transforming the NAS to attain TBO. This would be accomplished by incorporating air traffic controllers, pilots, ATMs, and aircraft systems. For operational benefits in the future, such as ADS-B In applications, searching and rescuing, possible conflict detection, radar separation, etc., installed ADS-B infrastructure can be utilized. With the infrastructure transformation and upgrade, new concepts will emerge and be supported.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACSS − Aviation Communication Surveillance Systems
ADS−B − Automatic Dependent Surveillance-Broadcast
ADS−R − Automatic Dependent Surveillance − Rebroadcast
AI −Artificial Intelligence
ANSP − Air Navigation Service Provider
ASAS − Airborne Collision Avoidance System
ASEPS −Advanced Surveillance Enhanced Procedural Separation
ASSC − Airport Surface Surveillance Capability
ATAS − ADS-B Traffic Advisory System
ATC − Air Traffic Control
ATM − Air Traffic Management
ATSAW − Airborne Traffic Situation Awareness
CAVS − Assisted Visual Separation
CDTI − Cockpit Display of Traffic Information
DME − Distance Measuring Equipment
EASA − European Union Aviation Safety Agency
EUROCAE − European Organization for Civil Aviation Equipment
EUROCONTROL − European Organization for the Safety of Air Navigation
FAA − Federal Aviation Administration
FIS−B − Flight Information Service-Broadcast
FMS − Flight Management System
GNSS − Global Navigation Satellite System
GPS − Global Positioning System
ICAO − International Civil Aviation Organization
IM − Interval Management
ITP − In-Trail Procedures
NAS −National Airspace System
NextGen− Next Generation Air Transportation System
NTSB − National Transportation Safety Board
PBN − Performance-Based Navigation
RTCA − Radio Technical Commission for Aeronautics
SESAR − Single European Sky Air Traffic Management Research
TBO − Trajectory-Based Operations
TCAS − Traffic Collision Avoidance System
TIS−B − Traffic Information Service-Broadcast
UAVs − Unmanned Aerial Vehicles
WAM −Wide Area Multilateration
1090ES/UAT − 1090 MHz Extended Squitter/Universal Access Transceiver

МОДЕРНИЗАЦИЈА И КОНТРОЛА ВАЗДУШНОГ САОБРАЋАЈА: ИМПЛЕМЕН–ТАЦИЈА АДС–Б СИСТЕМА 2022 – ПРЕГЛЕД

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Вишепараметарски систем за надзор, Automatic Dependent Surveillance – Broadcast (ADS–B), дизајниран је за унапређење кључних сегмената ваздушног саобраћаја: омогућавање надзора у реалном времену, повећање безбедности и ефикасности, као и побољшање летачких и метеоролошких информација. ADS–B се састоји од два подсистема, ADS–B Out и ADS–B In. Иако само комплетан систем ADS–BIn/Out омогућава бројне предности, као што су додатна свесност ситуације и ефикасније океанско рутирање, FAA и EASA захтеви односе се само на ADS–B Out (до јануара и јуна 2020. год.), при чему ADS–B In остаје опциони. Нема сумње да ће комплетан ADS–B In/Out систем бити у широкој употреби, али постоје неке слабости, које се превасходно односе на његове сајбер рањивости, узроковане недовољном аутентифи–кацијом и енкрипцијом у примењеном протоколу. У овом раду, дат је преглед ADS–B система, као помоћ у разумевању безбедносних проблема и различитих начина потенцијалних напада на ADS–B систем. Поред тога, овај прегледни рад бави се тренутним стањем у примени ADS–B, као и његовом будућом перспективом и изазовима.