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OpenSky Report 2021: Insights on ADS-B Mandate and Fleet Deployment in Times of Crisis

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***Abstract*—The year 2020 had been selected by EU and US regulators as the deadline for ADS-B compliant Mode S transponders, following various iterations of ADS-B and Mode S services. It will also be remembered as marking a profound change in civil aviation, when the global virus outbreak triggered an unprecedented slowdown in traffic and brought immense impact on the world economy. Fleets have been grounded and a great number of airplanes went into long-term storage due to travel restrictions. The OpenSky Network has been collecting valuable information regarding ADS-B compliance since 2017. It also acted as an important open data source for studying the aviation industry during these crisis times. In this paper, we analyze years of data collected by the OpenSky Network to provide an overview of the past and current situations in global air traffic with equipage updates, ADS-B implementation, Mode S interrogation practices, and fleet management by airlines.**

I. Introduction

The introduction of Automatic Dependent Surveillance–Broadcast (ADS-B) in the 2000s has been justified by the potential benefits of automatic broadcast of data by aircraft. Metrics enhanced by ADS-B include higher frequency and precision of an aircraft's information being available to Air Traffic Control (ATC) and neighbouring aircraft, cost reduction of ground infrastructures, and access to traffic information in remote areas via satellite. Beyond these planned capabilities which directly help Air Navigation Service Providers (ANSP) to improve air traffic surveillance, the unencrypted nature of ADS-B has enabled the large-scale collection of open air traffic data. In addition to the ability to continually track aircraft, open ADS-B and Mode S data provide researchers an important source of information that can be used to assess safety and compliance, predict flight trajectories, analyse performance of aircraft, and examine flight efficiency.

Through the *Title 14 Code of Federal Regulations (CFR) §91.255* issued in June 2010, the FAA set the ADS-B Out equipage deadline for January 1, 2020 on all aircraft with an electrical system in designated airspace [1]. In Europe, several changes have been proposed over the last ten years regarding the mandate deadlines. The European Commission issued Regulation 1207/2011 mandating the Single European Sky [2]. As part of this, ADS-B Out usage is mandated on aircraft built after January 8 2015 and for all aircraft by December 7, 2017. Regulation 1028/2014 later modified this, pushing the deadline to June 2020 [3]. After that, the deadline was pushed back again by Regulation 2020/587 [4], adding a transitional period and exemptions for older aircraft up to 2023 and 2025, respectively. ADS-B transponders have also evolved over the past two decades, where the three different versions (version 0, 1, and 2) are all being operated by different ADS-B compliant aircraft.

As one of the most common implementations of ADS-B, Mode S Extended Squitter (ES) is one of the most important technologies in air traffic surveillance. It supports the operation of secondary surveillance radar (SSR) and traffic alert and collision avoidance systems (TCAS). In Europe, depending on the weight category and flight rules, aircraft are required to be compliant with Mode S Elementary Surveillance (ELS) and/or Mode S Enhanced Surveillance (EHS). These Mode S interrogations from surveillance radars also vary across airspaces and regions, and OpenSky data provides the opportunity to take a look at differences and evaluations of Mode S interrogations.

The year 2020 will remain an important milestone in aviation not only because of the ADS-B mandate. With the Covid-19 outbreak, researchers have been using a comprehensive air traffic dataset, derived and enriched from the full OpenSky data [5] in order to analyse the effects of the pandemic and containment measures on economies [6]–[8], air quality [9], earthquakes [10], and more. The epidemic marked a severe slowdown in traffic, parked a lot of aircraft in storage, and plans for fleet management were updated with cancellation of orders and early retirements of aircraft.

In this paper, we build on the OpenSky Report 2016 [11] and leverage historical data to provide a comprehensive snapshot of the current state of aviation from various perspectives:

- The regulatory perspective: How did equipage upgrades unroll with respect to ADS-B mandates and versions?
- The service provider perspective: How have Mode S interrogation practices evolved over the past years?
- The operator perspective: How did airlines manage their fleet? Where did they store their aircraft? How did manufacturers experience the slowdown in aircraft production?

In Section II, we provide the background on OpenSky and ADS-B/Mode S capabilities. We then introduce the data collection process we performed in Section III, before analysing

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the current situation in Section IV. Sections V and VI discuss our findings and conclude this work.

II. Background and Methodologies

A. The OpenSky Network

The OpenSky Network is a crowdsourced sensor network collecting surveillance data for air traffic control (ATC). Its objective is to make real-world ATC data accessible to the public and to support the development and improvement of ATC technologies and processes. Since 2013, it has continuously been collecting air traffic surveillance data. Unlike commercial flight tracking networks (e.g., Flightradar24 or FlightAware), the OpenSky Network keeps the raw Mode S replies as they are received by the sensors in a large historical database, which can be accessed by researchers and analysts from different areas.

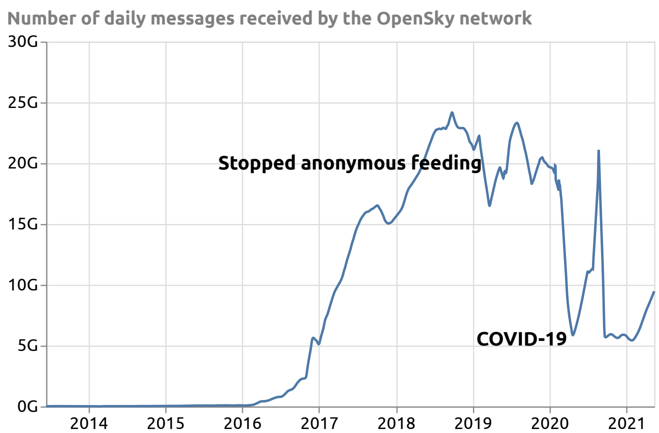

Fig. 1: The growth of OpenSky's dataset over time from 2013 to March 2021

The network started with eight sensors in Switzerland and Germany and has grown to more than 3000 registered receivers at locations all around the world. As of this writing, OpenSky's dataset contains seven years of ATC communication data. While the network initially focused on ADS-B only, it extended its data range to the full Mode S downlink channel in March 2017.[1] The dataset currently contains more than 22 trillion Mode S replies and, before Covid-19, received more than 20 billion messages per day. Fig. 1 shows the growth and development over the past several years, which saw the inclusion of the `dump1090` and Radarcape feeding solutions and the integration of non-registered, anonymous receivers, which has been discontinued early 2019 to further ensure the quality of the feeder data. In March 2020, the number of daily messages dropped to about 30% of the previous level, reflecting the curtailment of air travel around the world due to the Covid-19 pandemic. Recovery has been slow so far, and it may take years to return to the previous numbers.

Besides the payload of each Mode S downlink transmission, OpenSky stores additional metadata. Depending on the receiver hardware, this metadata includes precise timestamps (suitable for multilateration), receiver location, and signal strength. For more information on OpenSky's history, architecture, and use cases refer to [12], [13] or visit https://opensky-network.org.

[1]Currently, the RAW Mode S data is only available as of 2020 due to storage limitation. Older data will be restored when storage is upgraded.

B. ADS-B Versions and Common Mode S Capabilities

Since ADS-B was first implemented, there have been two different updates, resulting in a total of three versions, namely version 0, 1, and 2. Version 1 was introduced around 2008, where new message types, such as aircraft status (type code 28) and operational status (type code 31), were introduced. Version 2 was rolled out in 2012, which further refined and updated the structure of these two message types. Both updates brought more categories regarding accuracy and integrity of the navigation information.

The version information (1 or 2) can be decoded directly from the operational status message. Since version 0 transponders do not broadcast this message, the lack of type code 31 messages can be used to identify version 0 transponders. In this paper, we make use of this logic to determine versions of ADS-B compliant Mode S transponders.

Since ADS-B is only mandatory in certain air spaces around the world (e.g., Europe and United States), there are still a large number aircraft in the OpenSky Network that are not compliant with any existing ADS-B mandate. To identify these aircraft, we need to further analyze Mode S capabilities beyond extended squitter. To achieve this, we need to decode and analyze information contained in *common usage GICB capability report* (GICB) in ELS.

The analysis of Mode S capabilities requires a deeper understanding of Comm-B protocols. Comm-B, also known as *roll call reply*, is one of the most used downlink types in Mode S communication. It has the downlink format (DF) of 20 or 21. Both ELS and EHS use the Comm-B downlink. Each Mode S service has multiple types of downlink messages, which are distinguished by a Comm-B data selector (BDS) code. Table I lists the common Mode S BDS codes and associated message content [14]. BDS codes are not always included in every type of downlink message. However, they can be inferred based on a set of rules explained in [15].

GICB messages (BDS 1,7) are ELS messages used by secondary surveillance radars to obtain aircraft Mode S capabilities. Since they encode capability information regarding aircraft Mode S transponders, we can determine how they are equipped globally by using Mode S data from all around the world, especially when combined with global data from the OpenSky Network.

III. Data Collection and Processing

A. Data Collection

1) ADS-B operational status from January 2017: Since 2017 OpenSky started to collect full ADS-B operational status messages (type code 31). Hence, we can use the data to perform ADS-B version analysis. In this study, for every eight days since 1st January 2017, we downloaded one day of

TABLE I: Overview of different Mode S messages and BDS codes

Type	BDS	Message
ES (ADS-B)	0,5	Airborne position
	0,6	Surface position
	0,8	Identification
	0,9	Airborne velocity
	6,1	Aircraft status
	6,5	Extended squitter aircraft operational status
ELS	1,0	Data link capability
	1,7	Common usage GICB capability
	2,0	Aircraft identification
	3,0	ACAS resolution
EHS	4,0	Vertical intention
	5,0	Track and turn
	6,0	Heading and speed

operational status messages. Since the information contained in operational status does not change often, we keep only one operational status message per hour per aircraft. The resulting dataset consists of 38 million messages. The data is combined with an aircraft database where each known transponder address is mapped with the aircraft type and operator.

2) Mode S GICB data from January 2020: Limited by storage capabilities, the OpenSky Network currently provides readily available raw Mode S data since January 2020. Since the size of roll call data is quite large, we extracted a sampled dataset from the database. For every four days since the 1st of January 2020, we extracted a two-minute sample of all roll call data in the network for every 30 minutes. This created a dataset consisting of approximately one billion raw Mode S messages. After these raw messages are collected, we apply the BDS inference process [15] to extract GICB messages, which resulted in a GICB dataset consisting of 24 million messages. Then, Mode S capabilities in all GICB messages were decoded and stored for the analysis.

3) Global flight movements from January 2019: This dataset presented in detail in [5] was originally created for research on air traffic movements during the Covid-19 pandemic and is still maintained. It spans all flights seen by the network's more than 3000 receivers between 1st January 2019 and 1st May 2021. The archive is being updated every month and for the first 18 months includes 41,900,660 flights, from 160,737 aircraft, which were seen to frequent 13,934 airports in 127 countries. It contains no trajectory information, only the first and last positions of each flight, with a mapping to the closest known airport. The decoding and flight derivation process is detailed in the accompanying paper [5].

IV. Analysis

A. Mode S in Practice

By analyzing the GICB, we are able to generate statistics regarding Mode S Comm-B capabilities for all aircraft known to the network. In Fig. 2, all available capabilities are decoded and shown. Here, we assume that all Mode S transponders are capable of transmitting ELS BDS 2,0 messages (aircraft identification) since this is one of most basic messages in Mode S. Based on this figure, we can conclude that ADS-B capable aircraft (with BDS from 0,5 to 0,9) count for more than half of all aircraft.

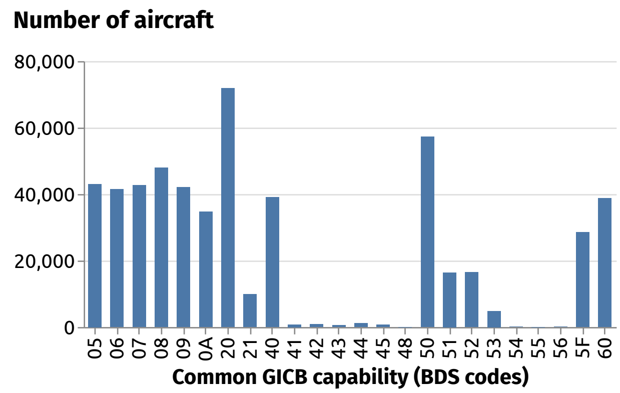

Fig. 2: Overview of global GICB capabilities

It is also worth noting that there are other BDS codes, which do not belong to the three groups in Table I. For example, BDS 4,4, and BDS 4,5 are messages from Mode S meteorological service. Nevertheless, these are common Comm-B messages that the surveillance radars often interrogate.

By comparing these BDS codes with Mode S services in Table I, we can study ES (ADS-B) and EHS compliance among all aircraft known to OpenSky network. We consider an aircraft is ES or EHS compliant if at least one ADS-B or Mode S message type is detected. This result is shown in Fig. 3. We can see that over around 68% of the aircraft are equipped with ADS-B capable transponders, and around 81% of the aircraft are compliant with EHS requirements.

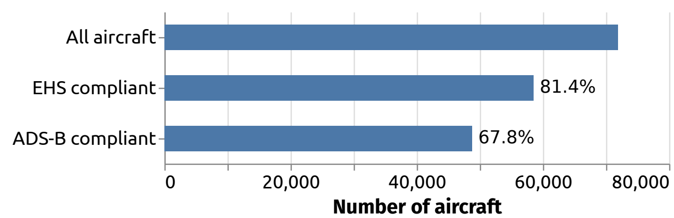

Fig. 3: ADS-B and EHS compliance among all known aircraft

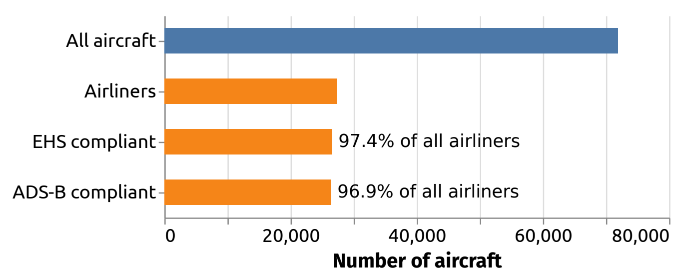

Fig. 4: ADS-B and EHS compliance among all known commercial aircraft

It is worth noting that the result in Fig. 3 includes all aircraft, such as helicopters and general aviation airplanes. Fig. 4 details the statistics based on aircraft owned by commercial operators. We can see that around 97% of all airliners are both ADS-B and EHS compliant.

Upon closer examinations, we discover that almost all airliners that are not ADS-B compliant belong to Embraer ERJ family. The statistics of the top airlines with these non-compliant aircraft are shown in Fig. 6.

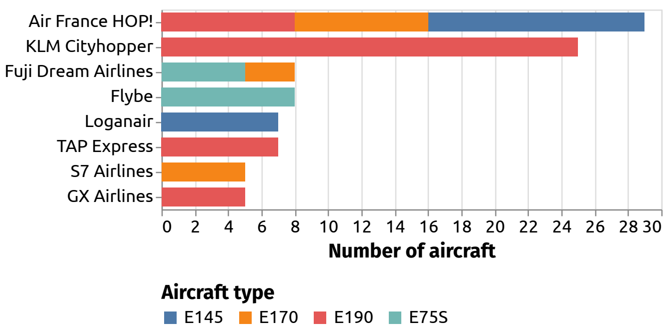

Fig. 6: Top airliners that are not ADS-B compliant (as of March 2021)

Mode S capabilities can vary depending on the aircraft type. To further demonstrate this, Fig. 5 shows the top 50 most common aircraft type and their Mode S capabilities. Almost all commercial airliners supports ADS-B, while only a small portion of general aviation aircraft are equipped with ADS-B transponders. The difference in other types of Mode S capabilities can also be distinguished in this figure.

B. New Transponders

As the OpenSky network has been tracking ADS-B operational status since 2017, it is possible to study the evolution of ADS-B transponder versions over the past few years.

For the analysis in this section, we focus only on commercial aircraft. Fig. 7 shows the statistics of transponder versions in new aircraft.[2] We see that a number of version 0 and version 1 transponders were introduced before 2018. Since then, the majority of transponders are compliant with the newer ADS-B version 2.

At the same time, a small number of new aircraft with version 0 transponders still appear since 2018. These aircraft are likely to be existing aircraft detected by the network as its geographic coverage increased. They may also include aircraft that have been sold to a different operator and assigned with a new transponder code matching the new country specifications.

Another interesting observation is the sharp reduction in new aircraft since March 2020, when the Covid-19 pandemic started, which is further analysed in the later sections.

C. Equipage Update

With the same dataset, we can also analyze the update of ADS-B equipment. By looking at the ADS-B version history

[2] More accurately, these "new" aircraft are the ones new to the OpenSky network, for example, due to increased geographic coverage.

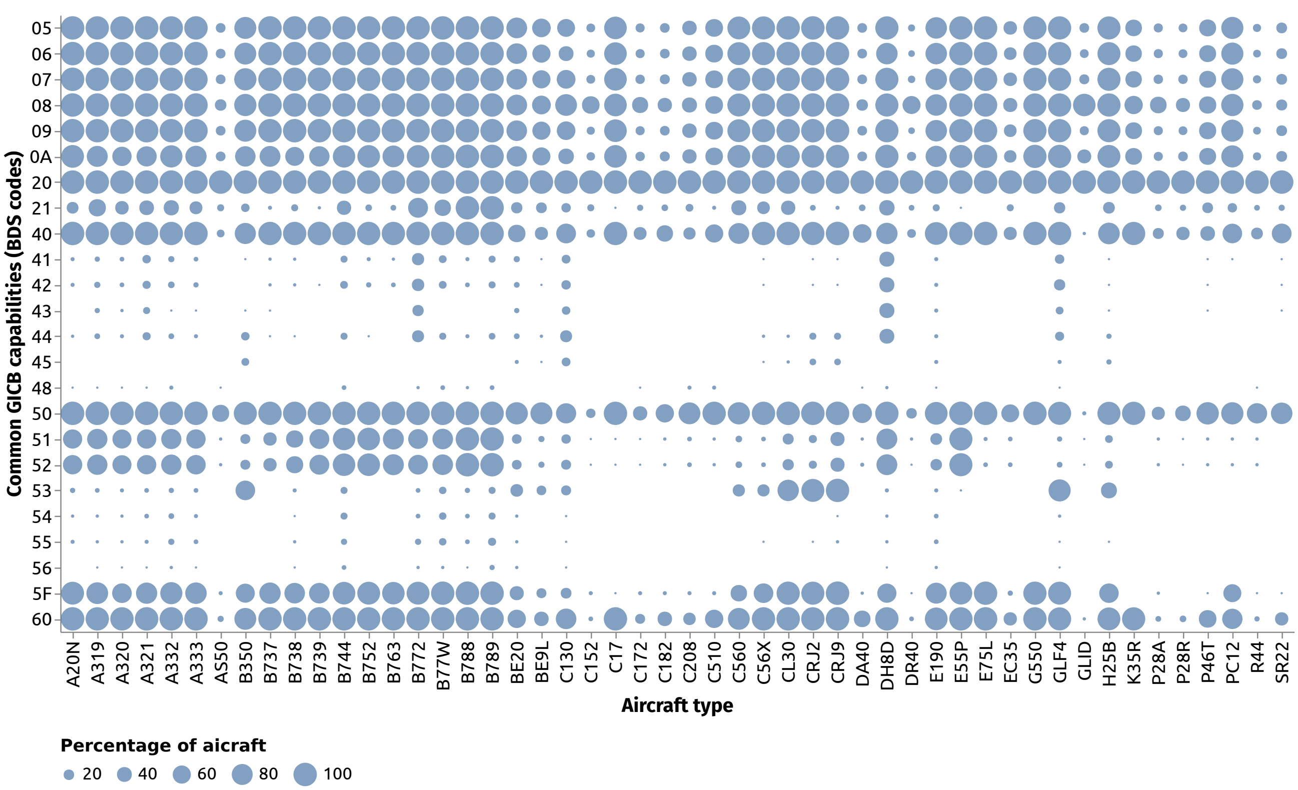

Fig. 5: Commonly supported Mode S capabilities among top 50 aircraft types

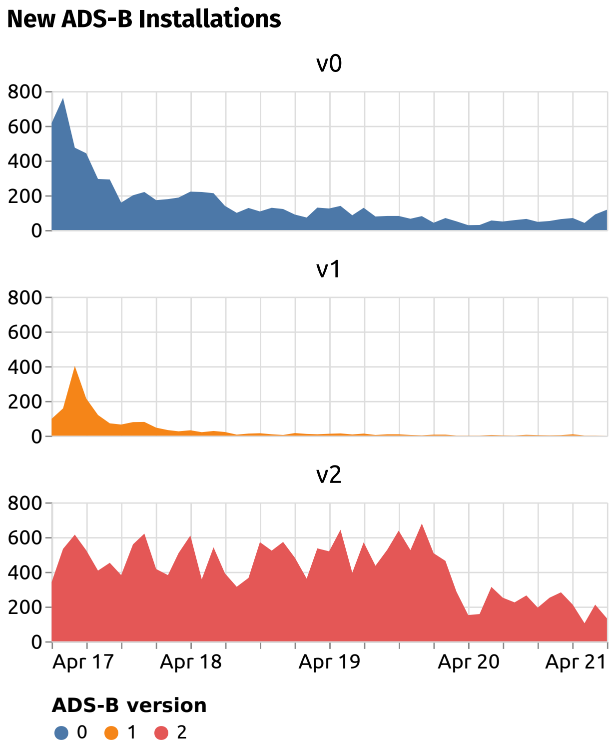

Fig. 7: ADS-B versions in new aircraft from 2017

of each aircraft, we extract the time (rounded to the month) when transponder version changes occur.

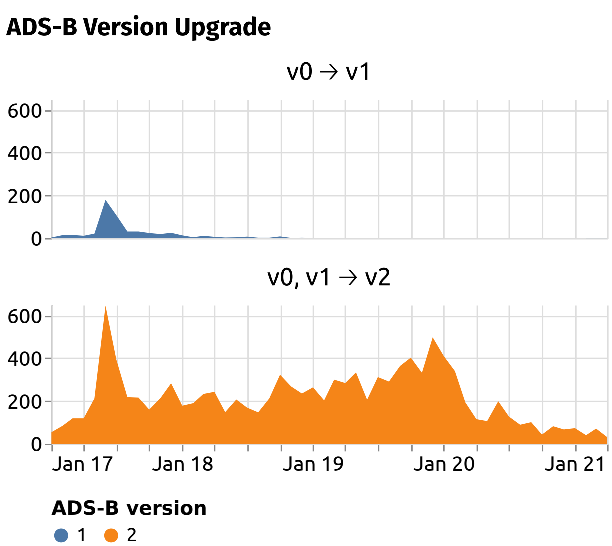

Fig. 8: Transponder ADS-B version updates from 2017

Fig. 8 shows the update from version 0 to version 1 and the update from version 0 or 1 to version 2 since 2017. Similar to Fig. 7, we see the update to version 2 slows down after 2020. However, a clear upward trend of updating to version 2 since 2018 is distinguishable. This corresponds to the 2020 ADS-B mandate for aircraft in both Europe (even though it has been extended) and the United States.

If we take a look at the updates for a few major airlines in the United States and Europe as shown in Fig. 9, this trend is clear. We can see that large airlines such as American Airlines, Delta, Lufthansa, and United Airlines all scheduled the update of their transponders before 2020.

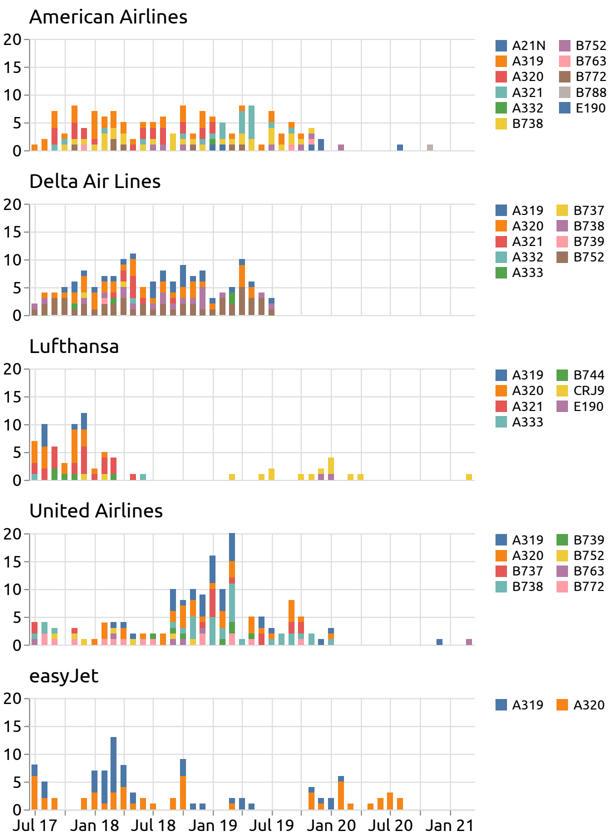

Fig. 9: Transponder updates among selected airlines

For comparison purposes, we selected a European low-cost airline. Since the ADS-B mandate was delayed until beyond 2020 in Europe, it is possible to see that easyJet has also delayed the update of their transponders accordingly. We also notice some outliers in the previous figure, where the update occurs much later than the 2020 US mandate. Upon closer inspection, they turn out to be new aircraft reusing old transponder identifiers.

D. Two Years in Commercial Aviation

The year 2020 was always expected to be an important milestone in aviation because of the ADS-B mandate issued by the FAA and the European Union. Beyond this planned impact, two crashes of Boeing 737 MAX in late 2018 and early 2019 impacting Lion Air and Ethiopian Airlines triggered a massive immobilisation campaign. 2019 further marked the 50th birthday of the Boeing 747 "*Queen of the Skies*" and the beginning of retirement campaigns for airlines switching to less fuel-consuming modern wide body aircraft like the new Boeing 787 "*Dreamliner*" (2009) or Airbus 350 family (2013).

The start of the COVID-19 pandemic in early 2020 then dealt a severe blow to the whole aviation world, cut worldwide passenger traffic [5] and immobilised many aircraft, with airport runways converted into storage spaced. The pandemic also had a serious impact on aircraft sales and on fleet management strategies with airlines accelerating their fleet renewal, considering early retirement for their B747 or Airbus A380 super wide-body aircraft.

a) The Boeing 737 MAX Woes: After the Ethiopian Airlines crash on March 10, 2019, the FAA was one of the last entities to issue a grounding order regarding all Boeing 737 MAX on March 13. Fig. 11 reflects this abrupt change from March 2019. Few flights occurred after mid-March, mainly to relocate aircraft or for Boeing to perform test flights from their Seattle facility. December 2020 marked a slow resuming of operations; a large share of Boeing 737 MAX flights are still operated under a BOE callsign.

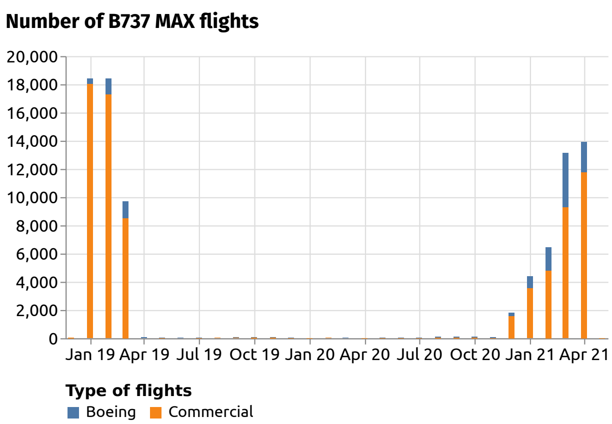

Fig. 11: Number of monthly flights conducted by Boeing 737 MAX aircraft

Table III highlights a number of Boeing 737 MAX aircraft stationed in a given airfield for an extended time. Negative delta values reflect more aircraft landing than taking off (from April to December 2019) while positive delta values show more aircraft taking off than landing (after October 2020). Coverage is a topic under continuous improvement with

TABLE II: Storage airfields for Boeing 737 MAX aircraft

	delta		country
KBFI	-136	Boeing Field King County Seattle	United States
KMZJ	-16	Marana Pinal Airpark	United States
KGYR	-13	Phoenix Goodyear Airport	United States
KSKF	-11	Lackland Air Force Base San Antonio	United States
LEDA	-7	Lleida-Alguaire	Spain
KPAE	-7	Snohomish County (Paine Field) Everett	United States
CYXX	-7	Abbotsford	Canada
KVCV	10	Southern California Logistics Victorville	United States
KMZJ	19	Marana Pinal Airpark	United States
KRNT	23	Renton Municipal Airport	United States
KTUL	24	Tulsa International Airport	United States

the OpenSky Network. As an illustration, Southern California Logistics Airport KVCV in Victorville did not appear as a place for aircraft to be stored in 2019 but emerged later as a source node where aircraft leave, similar to Renton Municipal Airport KRNT in Seattle where new Boeing 737 MAX aircraft are manufactured.

The sudden slowdown in terms of number of flights after the pandemic outbreak has already been widely documented, see for example the sources in [5]. Alongside the Boeing 737 MAX grounding, many other aircraft entered long-term storage in airline hub airports and in similar storage airfields. Fig. 10 shows satellite views in 2020 and 2021 over three such airfields highlighted by Table III underlining our statistical ADS-B-backed observations.

Overall, the grounding of Boeing 737 MAX seems to not have had a major impact on airlines operations. Table III shows that for most airlines, B38M represents a small fraction of their total fleet. Fig. 12 plots operations per aircraft typecode (B38M being on top of the color stack) for two airlines based on their callsign identifier: AAL for American Airlines and SWA for Southwest Airlines. Both airlines were impacted in the few days after the grounding order. Southwest Airlines seems to have quickly compensated for this loss with existing Boeing 737-700 aircraft, some of which seem to

Fig. 10: Satellite views of three storage airfields (not limited to Boeing 737 MAX): from left to right, Southern California Logistics Airport (KVCV), Phoenix Goodyear Airport (KGYR) and Pinal Airpark (KMZJ)

TABLE III: Top airlines owning aircraft of type B38M, B39M and B3XM

operator	B3*M	total	
Turkish Airlines	11	394	THY
flydubai	12	88	FDB
Copa Airlines	13	210	CMP
WestJet	13	211	WJA
GOL Linhas Aereas	15	434	GOL
Air Canada	19	234	ACA
TUI	20	347	TUI
Smartwings	21	178	TVS
United Airlines	30	875	UAL
American Airlines	40	1075	AAL
Southwest Airlines	58	832	SWA

have been borrowed from fellow airlines until the Covid-19 outbreak.

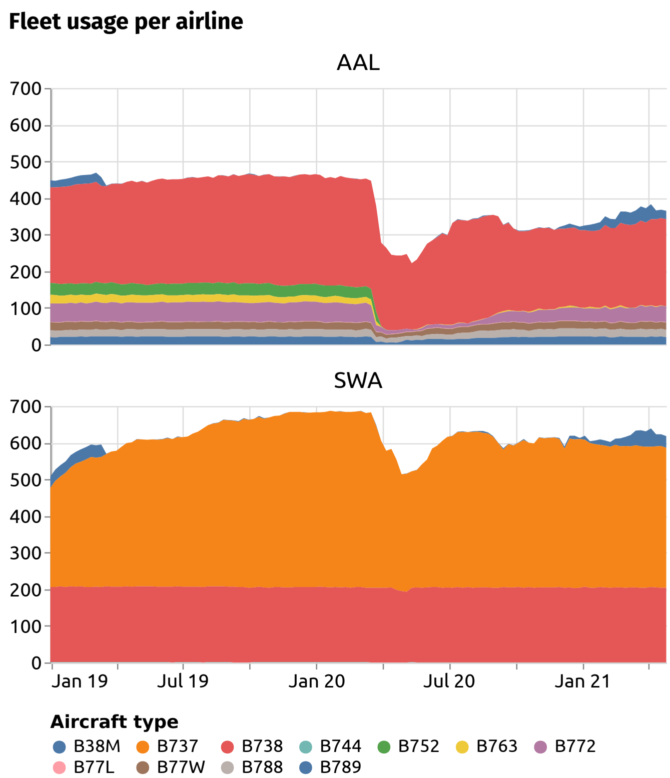

Fig. 12: Fleet usage between January 2019 and April 2021 for two major Boeing 737 MAX users: American Airlines and Southwest Airlines

b) Early Retirement & Replacement: While some airlines had already planned to retire their Boeing 747 fleet in the long run as they ordered more modern aircraft, the dramatic reduction in passenger flights after April 2020 accelerated the trend. Table IV reflects the number of aircraft from the Boeing 747 family with the date of their latest flight. It appears from the first table that KLM, Qantas, British Airways, and Virgin Atlantic retired some of their fleet. Last dates closer to 2021

TABLE IV: Last seen B747 grouped by operating airline

code	typecode	icao24	operator	last flight
KLM	B744	11	**KLM**	2019-04-12
QFA	B744	8	**Qantas**	2019-06-03
BAW	B744	34	**British Airways**	2019-06-24
VIR	B744	8	**Virgin Atlantic**	2019-11-22
THA	B744	8	**Thai Airways**	2020-02-26
DLH	B744	11	**Lufthansa**	2020-03-28

airport	icao24	last flight		
EHAM	3	2019-04-12	KLM	Amsterdam Schiphol
EGBP	1	2019-12-08	KLM	Cotswold
KORD	4	2020-05-25	KLM	Chicago O'Hare
KMCI	1	2020-12-07	KLM	Kansas City
LLBG	1	2021-01-18	KLM	Ben Gurion
KHHR	2	2019-06-03	QFA	*mismatch for* KLAX
KRIR	1	2020-02-13	QFA	*missing data before* KMHV
KLAX	5	2020-04-05	QFA	Los Angeles
EGDX	2	2019-06-24	BAW	St. Athan
EGFF	2	2019-11-17	BAW	Cardiff
EGLL	7	2020-02-28	BAW	London Heathrow
EGBP	7	2020-04-14	BAW	Cotswold
EGTW	2	2020-09-11	BAW	Oaksey Park
EGHQ	2	2020-10-18	BAW	Newquay Cornwall
EGTD	2	2020-10-22	BAW	Dunsfold

may suggest some aircraft only temporarily stopped operating, waiting for normal activity to resume.

Taking a more in-depth look at our collected data, KLM started retiring their older aircraft from early 2019. Aircraft doing their final flight to Amsterdam airport EHAM were actually all ferried to Teruel, Spain where aircraft are stored or recycled, but their trajectory does not appear on the OpenSky Network, probably due to some adjustments done on the transponders before the final flight. Qantas fleet was all disposed in Mohave airport in the Californian desert, out of coverage of receivers of the OpenSky Network. Flights to Los Angeles airport are usually well tagged, with a potential mismatch with neighbouring KHHR airport, but the final leg is often missing. Coverage over the UK being much more comprehensive, St. Athan and Cotswold storage facilities appear clearly in the table.

In the following, we first select timestamps when new transponder icao24 identifiers appear in the flight list. This approach selects not only new aircraft coming out of the factory but also those reassigned a different transponder matching the registration in the country of the owner. As a matter of fact, specific temporary registration numbers and transponder identifiers are used by manufacturers for the first flight of new aircraft,[3] but Table V suggests that manufacturers install the new transponders in their facilities for most airlines. Good OpenSky coverage in the Seattle area helps to identify the

[3]For example, F-W tail numbers usually apply to brand new Airbus, ATR, Dassault or Daher aircraft, with a 0x38 identifier reserved for aircraft registered in France.

TABLE V: Aircraft transactions between February 2019 and April 2021

			Airbus
ZGSZ	A20N	*79*	*Shenzhen Bao'an*
EDHI	A20N	165	Hamburg–Finkenwerder
LFBO	A20N	215	Toulouse–Blagnac
EDHI	A21N	320	Hamburg–Finkenwerder
LOWW	A320	*34*	*Vienna*
EDHI	A320	70	Hamburg–Finkenwerder
EDHI	A321	62	Hamburg–Finkenwerder
LFBO	A359	111	Toulouse–Blagnac
			ATR
LFBO	AT76	32	Toulouse–Blagnac
			Boeing
KRNT	B38M	127	Seattle Renton
ESSA	B738	*32*	*Stockholm–Arlanda*
LIME	B738	*32*	*Milan Bergamo*
KSEA	B738	36	Seattle Tacoma
EGSS	B738	*63*	*London Stansted*
KPAE	B763	44	Seattle Paine Field (Everett)
KPAE	B789	111	Seattle Paine Field (Everett)
			Bombardier
CYMX	CRJ9	39	Montreal Mirabel
			Embraer
SBSJ	E75L	80	São José Dos Campos
			Pilatus
LSZC	PC12	65	Buochs

airport where the production facilities for each Boeing series are located: Boeing 737 MAX in Renton KRNT, B767 and B787 *Dreamliners* in Everett KPAE north of the city.

Other airports in italics are major hubs for low-cost airlines who seem to handle their transponders themselves: Lauda in Vienna, Norwegian in Stockholm, Ryanair in London Stansted, etc. A few Chinese airlines join forces in Shenzhen airport for the same activities. A more in depth analysis of transponder identifiers disappearing in airports and new identifiers appearing with a different callsign identifier or being reused after a long period of inactivity could be performed to follow aircraft transactions more closely [16].

In spite of this strategy not fully capture the characteristic of aircraft production, it can give a hint at the number of aircraft transactions happening over a given time period. Fig. 13 plots the number of transactions per month for major aircraft types. April 2020 marked not only a serious slowdown in passenger activities. Even for Boeing 737 series, aircraft sales plummeted before slowly coming back to half the pre-COVID pace before the end of the year.

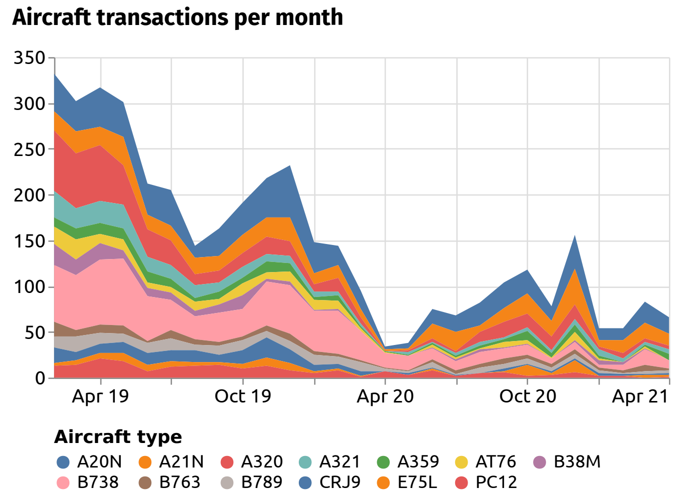

Fig. 13: Aircraft transactions between February 2019 and April 2021

V. Discussion

A. ADS-B Mandates & Regulatory Perspective

Finally, we want to update the overview on the ADS-B mandate since our first OpenSky Report five years ago. We focus mainly on the US and Europe, where OpenSky has the most dense coverage. In 2016, SSR Mode S was already widely operational around the world, including the US and Europe. ADS-B, on the other hand, was still in its rollout and deployment phase, with only around 7-8% of GA and commercial carrier aircraft officially equipped in the US at the time. In contrast to 2016, public statistics exist for equipage in Europe now, provided by the SESAR project. [17]

Fig. 14 illustrates the updated mandate timeline for ADS-B equipage in Europe and the US. Here, we can see that the FAA's CFR91.225 (issued in June 2010), originally set the ADS-B Out equipage deadline for January 1, 2020. Indeed, this pre-pandemic deadline was not moved or weakened as reports of grounded non-equipped aircraft also illustrate. Narrow exceptions were only authorized for non-ADS-B equipped aircraft used for national defense, homeland security, and law enforcement purposes.[4]

In Europe, the European Commission originally issued Regulation 1207/2011 mandating the Single European Sky. [2] As part of this, ADS-B Out usage was mandated on aircraft built after January 8, 2015, and for all aircraft by December 7, 2017. Regulation 1028/2014 later modified this to bring it in line with FAA efforts, pushing the deadline back to June 7, 2020 [3]. While Mode S ELS is now mandatory, the ADS-B mandate deadline was pushed back further in April 2020 due to the impact of Covid-19 on aircraft operators, to December 7, 2020.

Some wide-ranging exceptions to this date were permitted. Most notably, the ADS-B mandate only applies for aircraft with new Certificates of Airworthiness (C of A). Aircraft with a pre-existing CoA have until June 7, 2023 under transitional

[4]https://www.faa.gov/nextgen/equipadsb/govAuth/

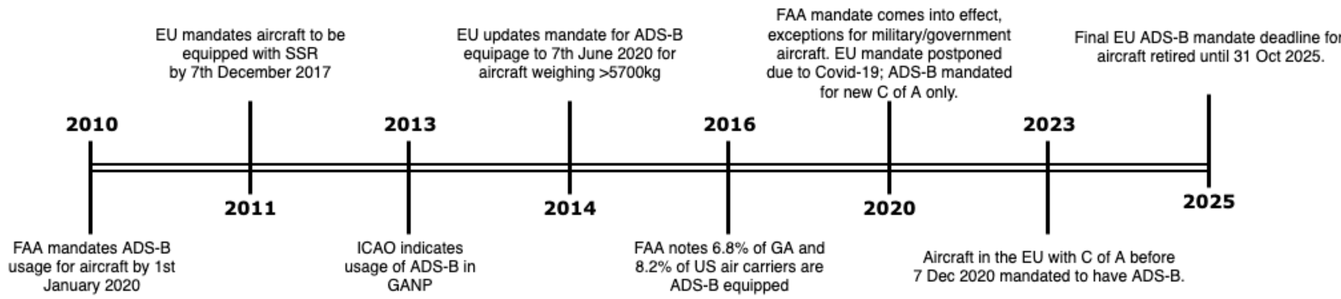

Fig. 14: Development of ADS-B mandates in the US and EU

arrangements for retrofitting. Aircraft that are being phased out and retired before October 31, 2025 will not have to retrofit at all (see Fig. 14).

Current equipage numbers are available for both airspaces. The SESAR project counts 84.8% of aircraft registered in EU27+4 with ADS-B Version 2 as of February 2021. [17] The FAA observes 145,416 successful ADS-B installations in May 2021, or 95.2%. [18] Official numbers on aircraft or flights with exceptions to the mandate are not available.

A cursory check of ADS-B mandates in other airspaces reveals a patchy landscape. Other countries and territories with ADS-B Out mandate and proposals include Australia, Canada, China, Colombia, Hong Kong, India, Indonesia, Malaysia, Mexico, Mongolia, Saudi Arabia, Seychelles, Singapore, South Africa, Sri Lanka, Taiwan, UAE, Vietnam, and New Zealand. [5] [6] Some countries have fixed deadlines far into the future but others with closer deadlines have seen deadline extensions, including New Zealand, which has postponed full mandatory adoption to 2023.

B. Critical Appreciation of Open Data Research

Using ADS-B and Mode S as a single source of information is tempting, as it is easier for researchers and the general public to measure much non-critical information about all stakeholders in the aviation world. Limitations coming with this approach have to be kept in mind, starting with non-universal coverage of the underlying data sources and an ADS-B mandate that is not yet fully implemented. Aircraft databases on which this work is based are also hard to consistently maintain, even though most information is in principle freely available on social network services and plane spotters websites.

Hence, there is no such thing as an omniscient source of information, and extracted information has to be taken with extra caution, especially when data processing tools are dependent on each other. ADS-B data provided by networks such as OpenSky are a precious tool to detect trends and offer data to the community, but such analysis calls for crosschecking with other sources of information, such as other ADS-B networks, press articles, or limited access information from service providers.

[5]https://www.aopa.org/go-fly/aircraft-and-ownership/ads-b/where-is-ads-b-out-required

[6]https://www.universalweather.com/blog/ads-b-update-2021/

VI. Conclusion

In this paper, we analyzed several years of data collected by the OpenSky Network. We provided an overview of the historical development and the current situation regarding several aspects of global aviation. We have studied the status of the ADS-B implementation, including regulatory mandates and aircraft equipage updates. We have further discussed Mode S interrogation practices, and fleet management by airlines during the Covid-19 and Boeing 737 MAX crises. Despite some natural limitations, our analysis shows again the power and utility of large-scale crowdsourced aviation data in order to assess the utilization of airspaces around the world.

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