OpenSky Report 2019: Analysing TCAS in the Real World using Big Data

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***Abstract*—Collision avoidance is one of the most crucial applications with regards to the safety of the global airspace. The introduction of mandatory airborne collision avoidance systems has significantly reduced the likelihood of mid-air collisions despite the increase in air traffic density.**

In this paper, we analyze 250 billion aircraft transponder messages received from 126,700 aircraft by the OpenSky Network over a two-week period. We use this data to quantify equipage and usage aspects of Traffic Alert and Collision Avoidance System (TCAS) as it is working in the real world. We furthermore provide an overview of the methods used by OpenSky to collect, decode and store this data for use by other researchers and aviation authorities.

We observe that around 89.5% of the ADS–B-equipped aircraft have an operational TCAS. We further analyze the concrete usage of TCAS by examining several case studies where a loss of separation between aircraft has happened.

I. Introduction

Collision avoidance is one of the most crucial applications with regards to the safety of the global airspace. Since the introduction of mandatory airborne collision avoidance systems (ACAS) in the 1980s [1], they have helped reduce the likelihood of mid-air collisions despite a significant increase in air traffic density. In a recent survey among aviation professionals, it has been considered one of the most safety-relevant communications technologies on-board an aircraft [2].

Whilst there is no doubt as to the principal efficacy of ACAS, or more specifically its implementation, the Traffic Alert and Collision Avoidance System (TCAS), many details about its large-scale usage are not available. Under the current analytics system, pilots have to fill in a report if they encounter a TCAS resolution advisory during flight. Naturally, like any system relying purely on human reporting, the number of unreported cases is unknown and potentially very high. Collecting the true TCAS data broadcast by the aircraft themselves can help address these issues and improve the common knowledge about the efficacy of the current collision avoidance implementations.

With regards to collision avoidance, resolution advisories are naturally highly interesting, as they give direct insights into potential safety incidents and loss of separation.

Besides resolution advisories, traffic advisories can provide early indications of potential issues with the system. Finally, the equipage statistics regarding TCAS are of interest as they provide important information about the type and versions used by aircraft in the wild as well as the speed of upgrades and adoption.

In this paper, we provide unique insights into the global functioning of the collision avoidance system, and the data collection challenges that we encountered during the 7 years of operation of the OpenSky Network. We use a large set of crowdsourced surveillance data gathered by the network to analyze and quantify equipage and usage aspects of TCAS as it is working in the real world. We furthermore provide an overview of the methods used by OpenSky to collect, decode and store this data for use by researchers and authorities.

Concretely, we provide insights into the following topics:

- **TCAS Data Collection:** We explain our method of data collection as much of the relevant TCAS data is not simply broadcast (such as ADS-B) but instead has to be extracted from the Ground-Initiated Comm B (GICB) Registers.
- **TCAS Equipage:** Further, we analyze the OpenSky data set with regards to the TCAS versions (if any) used by the tracked planes.
- **TCAS Usage:** Finally, we look at the usage of TCAS in practice, providing several case studies. We analyze resolution advisories transmitted by aircraft and look at characteristics of the situations and the type of aircraft involved.

The remainder of this paper is organized as follows. Section II outlines the necessary background on the TCAS technology. Section IV describes the current state of the OpenSky Network and its newly-realized TCAS integration. Section VI provides statistics on the real-world equipage of TCAS while Section VII analyzes the usage and impact of its collision avoidance functions by examining several case studies. Section VIII discusses our experiences and finally Section IX concludes this work.

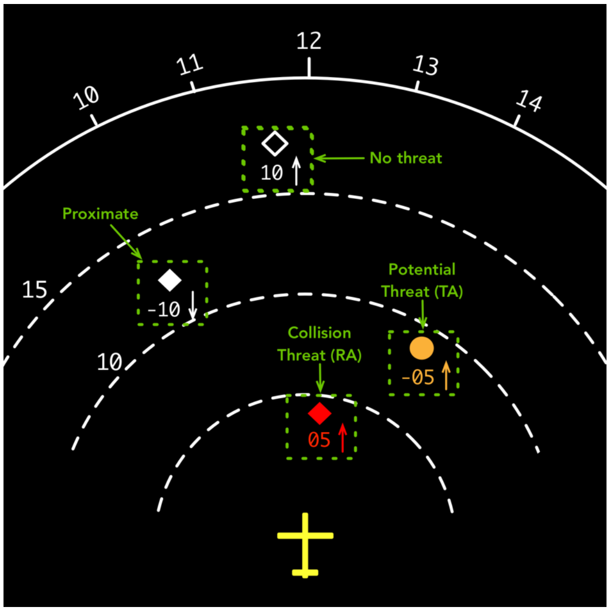

Fig. 1. A representation of TCAS data as seen by the pilot in the cockpit of an airliner. This is based on the Airbus Navigation Display (ND). Dashed semi-circles represent intervals at a range selected by the pilot, and numbers around the solid semi-circle are heading values.

II. Background: The Traffic Alert and Collision Avoidance System

Although airspace is tightly controlled by air traffic control (ATC), situations can arise where aircraft come too close to each other. This has resulted in mid-air collisions, such as the 1996 Charkhi Dadri crash, where an aircraft unduly descended and collided with another whilst under ATC control [3]. Incidents such as these have led to many regulators requiring aircraft to be equipped with collision avoidance systems, which may take over from ATC control when a dangerous situation arises.

TCAS is an implementation of the Airborne Collision Avoidance System (ACAS), designed to help reduce the chance of a mid-air collision [4], [5]. It has been required in some form on many aircraft since 1993, with TCAS II being introduced in 1998 [6]. In a situation where the risk of a mid-air collision is unacceptable (i.e. two aircraft are on course to collide soon), TCAS on each aircraft will communicate and negotiate actions for each aircraft [5].

The system on board the aircraft uses Mode C and S transmissions to detect and notify nearby aircraft of its existence, the responses from which are then processed and displayed to the crew. This will typically be presented as in Figure 1, with threats ahead of the aircraft being shown. Other aircraft can be *no threat*, *proximate*, a *potential threat* or a *collision threat*, depending on their distance, rate of closure and altitude difference. If an aircraft is a *potential threat*, a Traffic Advisory (TA) is given to crew, warning them of a potential intruder. If the intruding aircraft gets closer, a Resolution Advisory (RA) alert is given: the crew must ignore ATC instructions and follow the RA instructions.

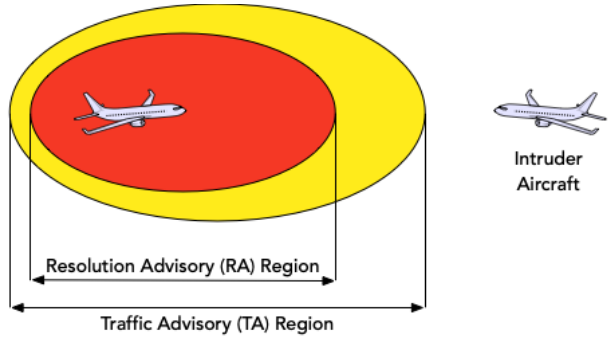

Fig. 2. Representation of TCAS Traffic (TA) and Resolution Advisory (RA) zones.

Although ATC manage airspace with high precision, aircraft can still end up closer than is safe. This is called a *loss of separation*, and in the worst case, can result in a mid-air collision. One such example occurred in March 2011, where a Delta aircraft took off with an inactive transponder, becoming too close to three other aircraft before resolving the issue [7]. TCAS provides a technical means by which to avoid this, and has been mandated on aircraft with more than 30 seats since 1993 [5], [6].

System Description

Establishing nearby aircraft with Mode S simply requires the object aircraft to listen for Mode S transmissions or 'squitters', the latter being messages transmitted periodically without prior interrogation. These contain the International Civil Aviation Organization's (ICAO) transponder IDs, so the object aircraft follows up with Mode S interrogations to establish the position of the nearby aircraft. Heading and range are determined using the object aircraft's directional antenna and the response time and altitude data is provided by the nearby aircraft from its instruments. Based on these data, the potential for conflict is calculated on the object aircraft. Depending on the proximity and closing speed of the target the interrogation rate will vary; at a large distance this will be once per five seconds, increasing to once per second when an aircraft is close [5]. An abstracted protocol diagram for Mode S can be seen in Figure 3 (top).

Mode C operates slightly differently, represented in Figure 3 (bottom). The object aircraft will issue Mode C-only all-calls, causing nearby aircraft with Mode C transponders to respond, at a rate of once per second. If the target has an altimeter then it will respond with its altitude, else TCAS onboard the object aircraft will use response characteristics to estimate altitude as well as range and bearing [5]. TCAS will only provide full alerting as below if Mode C-equipped aircraft provide altitude.

Through one of these methods, TCAS ascertains how close the nearby aircraft is both laterally and vertically, before deciding if it is necessary to alert the flight crew. For most systems, especially those on commercial aircraft, alerts are composed of two steps as shown in Figure 2. First comes a *traffic advisory* (TA), in which the traffic is typically displayed to the pilot as

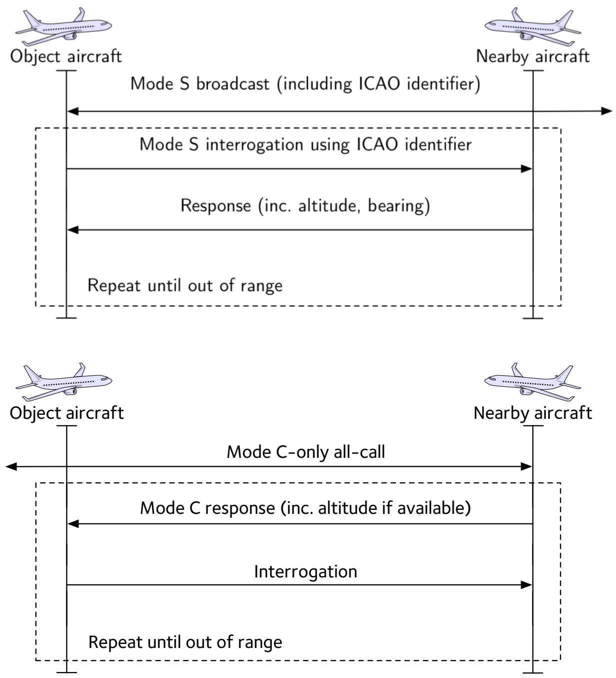

Fig. 3. Representation of TCAS interrogation protocols of nearby aircraft using Mode C and S transponders.

amber and an aural alert of ‘traffic’ is given. If the intruder becomes closer to the aircraft, a *resolution advisory* (RA) is given. An RA will contain specific instructions for the flight crew, i.e., to climb or descend at a given rate, or hold vertical speed. These instructions are decided between the two aircraft automatically and aim to deconflict the situation. Crew must follow the instructions of an RA within seconds.

In the cockpit, crew have some control over the sensitivity level; they can select *standby*, *TA-ONLY*, or *TA/RA*. For most of a flight, TCAS will be set to TA/RA, which automatically calculates sensitivity based on altitude. TA-ONLY is limited to the lowest sensitivity level and does not issue RAs, whereas standby performs no TCAS interrogations and will not resolve conflicts [5].

Whilst in TA/RA, TCAS will calculate the sensitivity based on altitude, with higher altitudes assigned higher sensitivities. This then defines the *tau* value for issuing a TA or RA. Tau is calculated as the time in seconds to the Closest Point of Approach (CPA) between object and nearby aircraft, either laterally or vertically. When the nearby aircraft is within tau, the relevant alert is given.[1] For example, between 5000 and 10,000 ft, tau for a TA is 40 s [5].

III. Importance of Separation

Adequate separation is a crucial component of effective and safe airspace with TCAS being in place to protect it. ICAO define vertical separation minima in Doc 4444, namely [8]:

[1]Some adjustments are made to this at lower altitudes, and are covered in detail in [5].

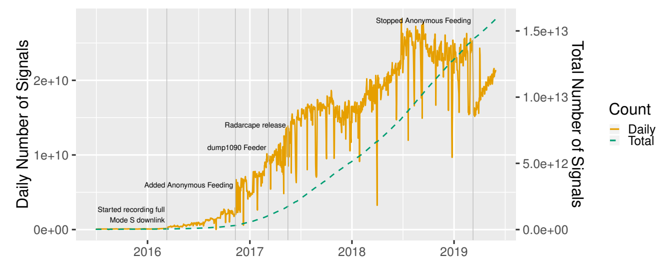

Fig. 4. The growth of OpenSky’s dataset over time from June 2013 to May 2019

- Under Vertical Separation Minimum (VSM), 1000 ft below 29,000 ft or 2000 ft above,
- In Reduced Vertical Separation Minima (RVSM) airspace in an RVSM-approved aircraft, separation above 29,000 ft is 1000 ft depending on conditions.

These are used as a basis by regional ATC in defining their requirements for VSM. Horizontal separation is a more complex definition which depends not only on the horizontal distance between aircraft but also on the vertical separation, type of navigation being used and whether the aircraft is climbing or descending [9].

Whilst losses in separation are not consistently penalized, they are treated as serious due to a potential ‘snowball effect’ if not corrected. A lack of separation allows for significantly smaller—or in some cases no—margin for error. In some cases these will be treated as an ‘airprox’, which requires a report on the incident to be submitted to a regional board.

Aside from the most serious consequence of separation loss, the mid-air collision, a number of other potential consequences can arise:

- Flight through wake vortex from other aircraft, causing extreme turbulence or loss of control,
- Causing other aircraft to take avoidance action, triggering airspace inefficiency,
- Requirement for extreme avoidance manoeuvres at short notice, risking injury to passengers or crew [10].

IV. The OpenSky Network

The OpenSky Network is a crowdsourced sensor network collecting air traffic control (ATC) data. 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 2012, it continuously collects 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.

The network started with eight sensors in Switzerland and Germany and has grown to more than 2000 receivers at locations all around the world. As of this writing, OpenSky’s dataset contains six 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, which is also the base for this present work. The dataset currently contains more than 15 trillion Mode S replies and receives more than 20 billion messages per day. Fig. 4 shows the growth and development over the past several years with milestones highlighted, including the support of the dump1090 and Radarcape feeding solutions and the integration of non-registered, anonymous receivers, which has recently been discontinued. 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 [11], [12] or visit http://opensky-network.org.

V. Data Collection

We decoded the Mode S replies using the latest version of OpenSky's open-source decoding framework libadsb[2]. Since OpenSky collects downlink transmissions only, the respective uplink interrogations containing the requested Ground-Initiated Comm B (GICB) register numbers are missing. Therefore, we have updated our decoding library with routines for detecting the registers that are relevant to analyse TCAS/ACAS advisories, mainly BDS 1,0 for equipage and capability information and BDS 3,0 for active resolution advisories.

The data set considered in this work is a snapshot of the unmodified data ("raw data") that came into OpenSky between May 10, 2019 and May 23, 2019. During this two-week period, almost 1000 sensors from over 90 countries reported around 250 billion Mode S signal receptions by 126,700 different aircraft to the network. Based on the reported altitude, we found around 44.6% of these aircraft to be capable of flying in Class A airspace, thus assuming that these flights operated under instrument flight rules (IFR). Aircraft that were only seen below flight level 180 are assumed to operate under visual flight rules (VFR). Fig. 5 shows the distribution of all replies across the different reply types and by IFR/VFR aircraft. VFR aircraft seem to be responsible for only a negligible fraction of the communication happening on the 1090 MHz frequency. This is not surprising since many rely on FLARM in Europe and UAT in the US and Mode S ground interrogators have very limited range on lower altitudes.

A. TCAS RA Detection

In order to find cases of active threat resolutions for our analysis, we searched the raw data for aircraft transmitting BDS 3,0 registers. Over the two weeks period, we found 147 situations where the TCAS units exchanged active resolution advisories. Besides the aircraft's own transponder ID and altitude, long ACAS replies containing BDS 3,0 registers also provide information such as the threat's transponder ID (or its range, bearing and altitude), whether there are multiple

[2]https://github.com/openskynetwork/java-adsb

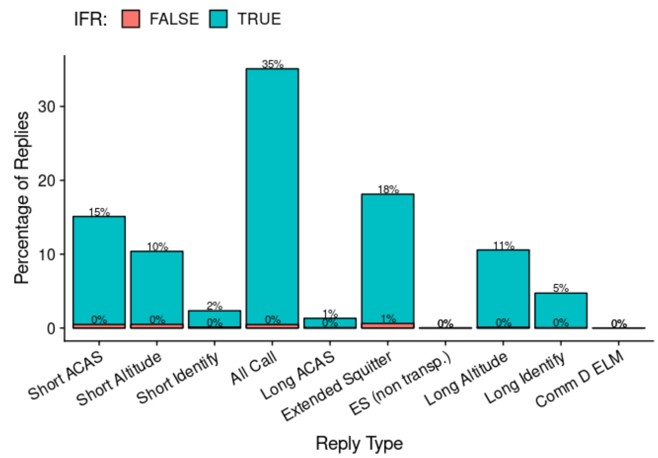

Fig. 5. Distribution of 249,310,882,072 Mode S replies collected by OpenSky during a two-week period 10-23 May 2019.

threats, and detailed information on the issued RA itself. The latter contains flags such as whether the RA is corrective or preventive, the "sense" of the RA (downward or upward), whether is constitutes a sense reversal, and others. Also complements to the RA such as "no pass below/above" or "no turn left/right" are included. In 106 of the 147 cases, the aircraft also transmitted ADS-B which enabled us to further investigate the spacial situation and behaviour before and after the issuance of the RA (see Sec. VII).

B. Aircraft Metadata

We have used OpenSky's own aircraft database to identify the metadata about an aircraft based on the received unique ICAO 24-bit identifiers. The aircraft database currently consists of 498,910 airframes (May 30, 2019), including about 1,500 different commercial airlines and many additional non-airline operators. The database has initially been built from many available online and offline sources, which are discussed in detail in the OpenSky Report 2017 [13]. It is now updated daily from several authoritative sources and also integrates crowdsourced information as it is curated by the wider OpenSky community. The full database is available for download and online use at https://opensky-network.org/aircraft-database.

C. Limitations

Despite collecting all analyzed data to the best of our possibilities, there are some natural limitations to the datasets used in our OpenSky reports. The most natural limit of our data is OpenSky's coverage. The OpenSky Network currently only fully covers the European continent (at least in the en-route airspace), while America, East Asia, Australia and New Zealand are covered partly. Our analysis explicitly does not cover or represent the situation in the non-covered airspaces.

Moreover, since receiving Mode S and ADS-B signals requires a line of sight between receiver and aircraft, the ranges of receivers are limited by the radio horizon. For example, if the aircraft is in the en-route airspace, i.e. at a high altitude, and the receiver is not obstructed by the geographical environment (e.g., in coastal areas), the radio horizon and thus the range can be up to 700 km. Aircraft at lower altitudes, however, remain difficult to track due to their reduced line of sight. As a consequence, lower altitudes are only covered if there is a sensor nearby and aircraft trajectories may be incomplete in many areas.

Another important limitation is the data quality. ADS-B is still in its deployment phase and there are no guarantees that transponders are functioning according to the specification. In fact, a small number of transponders broadcast erroneous or invalid positions, or wrong ICAO 24-bit addresses. Furthermore, most OpenSky receivers are not certified. Due to missing implementations of proper tracking techniques, erroneous messages can pass the error detection mechanism of Mode S and therefore end up in our data. Although we have a multitude of plausibility checks to filter most of these invalid data, a small amount may still remain in the data used for this work. Nevertheless, based on our experience from working with Mode S and ADS-B for many years, we are confident that the portion of erroneous data is negligible compared to the overall size of the dataset and that the numbers provided in this work are accurate estimates of the TCAS situation within OpenSky's coverage area.

VI. TCAS Statistics

A. Aircraft Equipage with TCAS

There are several possibilities to get information on TCAS equipage on the Mode S downlink. One way is to decode the ADS-B Operational Status reports of an aircraft, which include information such as ADS-B version, TCAS availability, ADS-B availability, use of multiple antennae or position accuracy information. This information, however, is only broadcast by an aircraft if the transponder supports it, i.e., only ADS-B version 1 and 2 transponders. Overall, we found that only about 43% of the aircraft in the data set reported their operational status.[3]. The other 57% used either ADS-B version 0 (11%) or no ADS-B at all (47%). Note that these numbers cover VFR flights as well as flights in countries with no ADS-B mandate. Because of the limited nature of the operational status reports, it is not meaningful for a broader analysis of TCAS. We thus propose a more accurate method to estimate TCAS equipage by analyzing the data set for the number of aircraft that were actually seen replying to TCAS interrogations. Overall, we observed replies from 89.47% of all transponder-equipped aircraft using this method, with minor differences between IFR (91.04%) and VFR (88.21%).

To get more details about the equipage, we also extracted BDS 1,0 GCIB registers from the 2-weeks Mode S data set. Among other things, BDS 1,0 provides information about the version of the TCAS transponder. Note that this method has limitations as well, since it requires the transponder to support Comm B data link transmissions and it requires a nearby interrogator requesting this specific BDS register. Nevertheless, we found information on 26,100 transponders. The distribution of the indicated TCAS versions of these transponders is shown in Fig. 6.

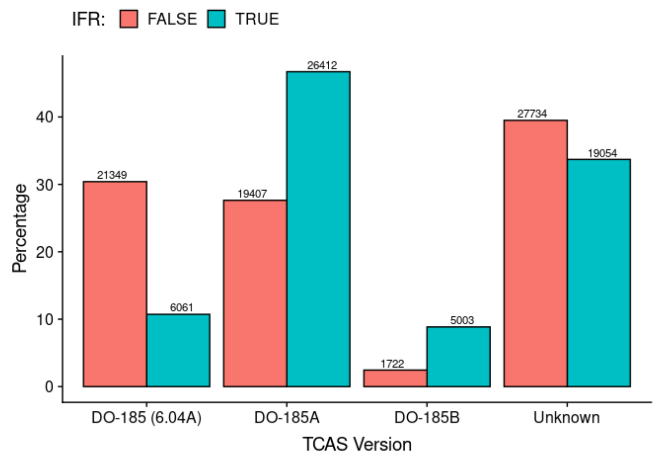

Fig. 6. Distribution of the TCAS versions indicated by 26,100 transponders in the respective BDS 1,0 GCIB transmissions.

TABLE I
Distribution of TCAS RAs by aircraft type (aircraft types with more than three occurrences).

A319	A320	A321	B737	B738	B739	B752
11	12	13	19	29	11	5
CRJ2	CRJ7	CRJ9	E75L			
17	5	10	21			

B. TCAS Usage Statistics

TCAS RAs by Aircraft Type: Table I shows the distribution of TCAS RAs by aircraft type. We have seen the most RAs for the B738 family, followed by the E75l and the B737. Naturally, these are absolute numbers, which must be seen in context, e.g. miles flown by these aircraft families within the OpenSky coverage.

TCAS RAs distribution by country: During the considered two-week period, TCAS RAs were collected for pairs of aircraft flying where OpenSky offers a coverage. 70 alerts were decoded over the United States, 15 over various Europe countries, 1 over Australia, 2 over Malaysia and 1 over Russia.

These figures have to be considered with caution. They should probably be normalised by a measure of traffic density and overall coverage of the considered region.

TCAS RAs distribution by altitude: Figure 7 plots the distribution of the altitudes where TCAS RAs occurred in the dataset and Figure 8 relates these occurrences to major neighbouring airports. Two major peaks in the distribution occur for altitudes very close to the ground, less than 3 nm from a major airport (see Section VII-A about parallel landings), around 10,000ft (see Section VII-B regarding intersections between traffic taking off and landing in neighbouring airports)

[3]An analysis of these status reports can be found in the OpenSky Report 2016 [14]

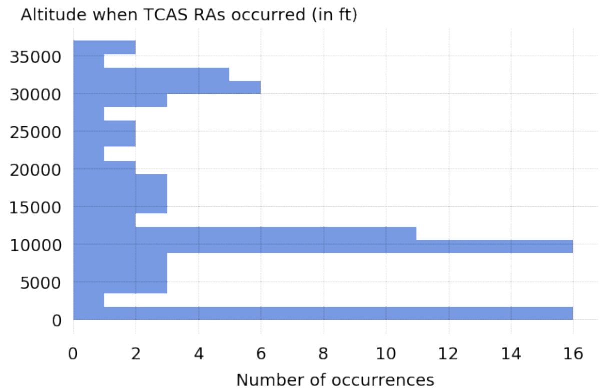

Fig. 7. Distribution of altitudes where TCAS RAs occurred.

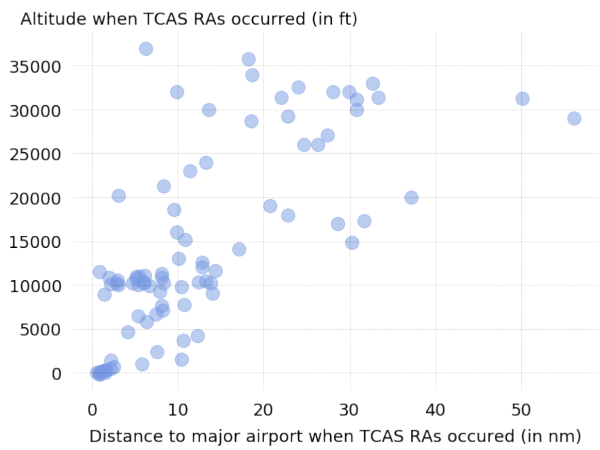

Fig. 8. Distribution of altitudes where TCAS RAs occurred vs. distance to major airport

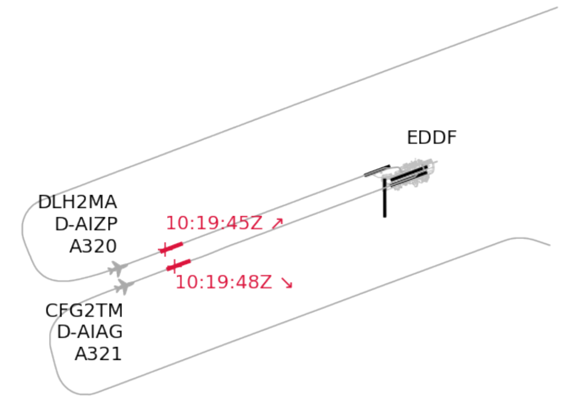

Fig. 9. Flight paths of DLH2MA and CFG2TM into Frankfurt Airport (EDDF) on parallel approaches. Parts of path marked in red indicate distance covered during a TCAS RA.

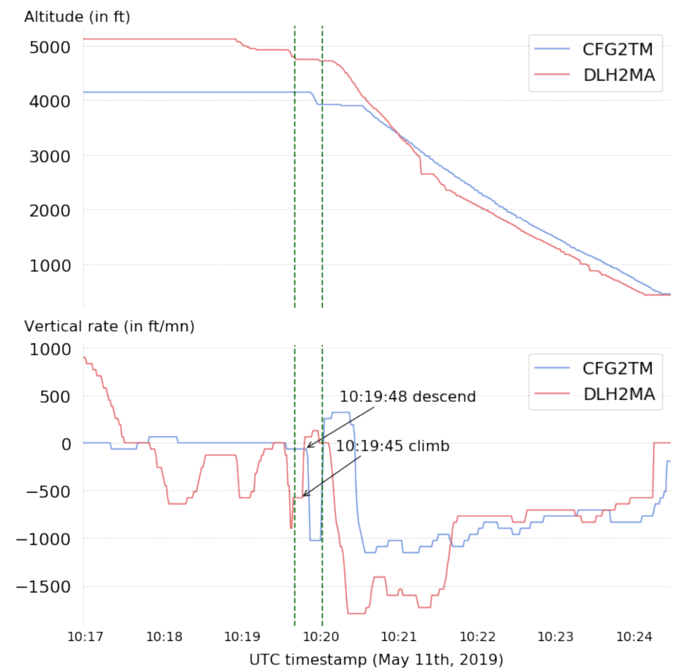

Fig. 10. Altitudes of DLH2MA and CFG2TM along with horizontal and vertical separation between the aircraft during the time period surrounding the RA on approach to Frankfurt Airport (EDDF). RA time period is denoted by green vertical lines.

with few occurrences around 30,000ft, near top of climbs and/or beginning of descents (see Section VII-C regarding the intersection between en-route traffic and climbing/descending aircraft).

VII. Case Studies

Our analysis has highlighted some examples of TCAS RAs which warrant further discussion. In this section we look at parallel approaches, at the intersection between standard arrival (STAR) and departure (SID) procedures, and near the top of climb/beginning of descent of trajectories.

A. Parallel Approaches

One situation in which TCAS appears to raise alarms under normal conditions is during parallel approaches. This is somewhat expected due to the relatively close proximity of aircraft at similar phases of parallel approaches and is usually safe considering that they are under close ATC management at this point.

In the case shown in Fig. 9 and 10, this is likely to have been triggered due to both horizontal and vertical proximity, coupled with the fact that the aircraft were at a sufficient altitude to use a higher sensitivity level. It appears that one aircraft was issued with a descend RA to increase separation. In this instance, whilst TCAS judged the situation to be a risk, it was not. According to METAR information at that time at Frankfurt airport `EDDF 111020Z 36009KT 9999 -RA FEW004 BKN009 11/09 Q1009 BECMG BKN010=`, moderate wind came from the North, which most probably lead to a heading of the aircraft not aligned with the runway (crab approach), possibly leading to an interpolation raising an alert.

In Fig. 11 and 12 we see another example of a TCAS RA on parallel approach. In this case, the RA is triggered as the

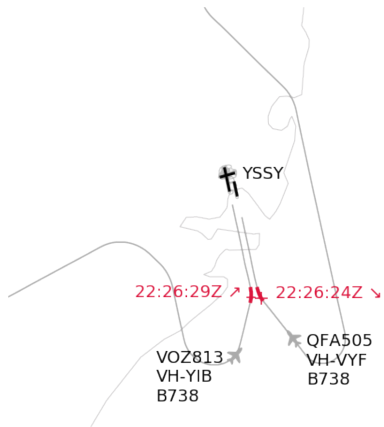

Fig. 11. Flight paths of VOZ813 and QFA505 into Sydney Airport (YSSY) on parallel approaches. Parts of path marked in red indicate distance covered during a TCAS RA.

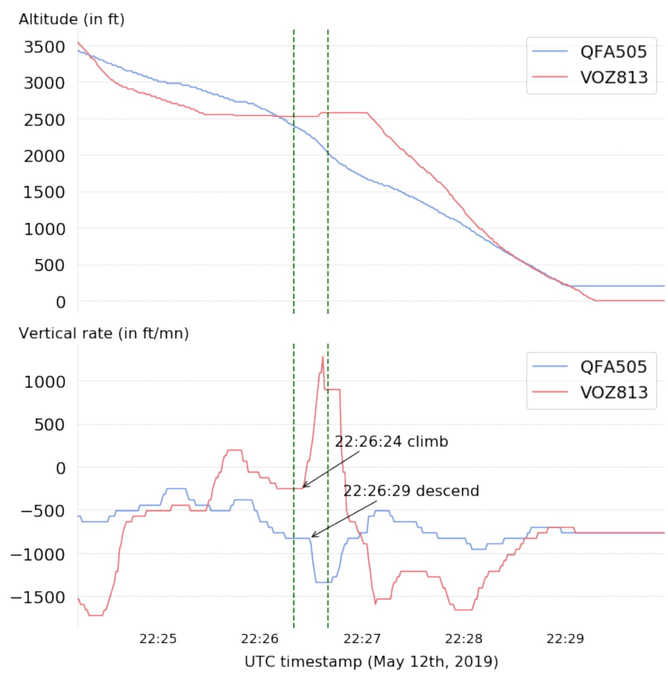

Fig. 12. Altitudes of VOZ813 and QFA505 along with horizontal and vertical separation between the aircraft during the time period surrounding the RA on approach to Sydney Airport (YSSY). RA time period is denoted by green vertical lines.

aircraft turn onto the localizers of their respective runways causing one aircraft to be issued with a maintain vertical speed (descend) RA and the other to maintain vertical speed (level) RA. Here, TCAS will have anticipated that the aircraft would have been continuing their localizer intercept paths, hence on course for collision. As with the previous case, the situation is safe and closely managed by ATC, but this RA is not spurious since the system accounts for intended future behaviour.

Unusual and anomalous final approaches have been addressed in [15] from a safety risk assessment point of view. In this specific situation, QFA505 reached 2500ft in order to catch

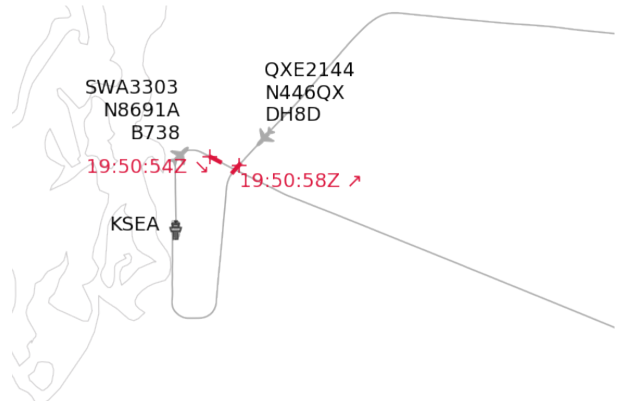

Fig. 13. Flight paths of QXE2144 and SWA3303 around Seattle–Tacoma Airport (KSEA) on intersecting departure and arrival trajectories. Parts of path marked in red indicate distance covered during a TCAS RA.

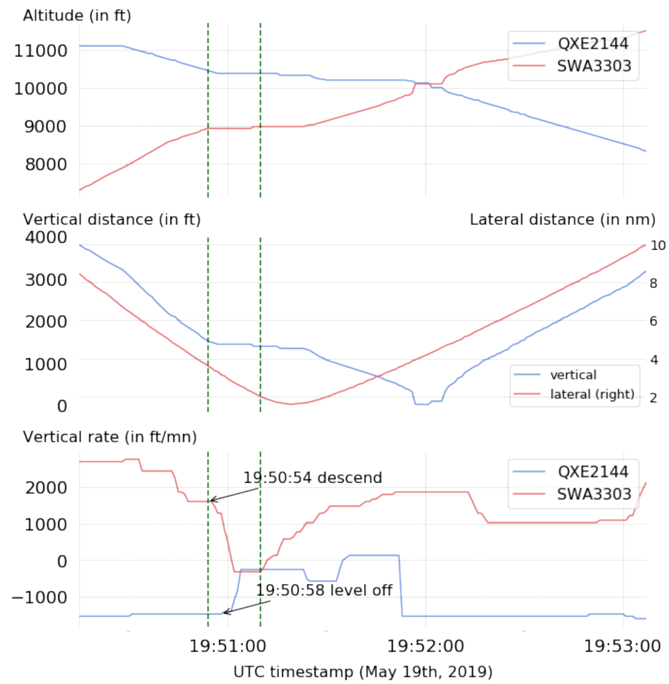

Fig. 14. Altitudes of QXE2144 and SWA3303 along with horizontal and vertical separation between the aircraft during the time period surrounding the RA on departure from/arrival to Seattle–Tacoma Airport (KSEA). RA time period is denoted by green vertical lines.

the glide path before landing. When the RA was triggered, they had to climb again, and came above the glide path. After the RA was resolved, the vertical rate came down to -1500ft/min and the aircraft caught the glide path from above around 750ft above ground. Losing that amount of total energy in the last miles before the runway threshold can be uncomfortable for the pilot and is a common cause of failed approach. It is also worth noting that final approaches and low altitudes are among the most common scenarios where RAs are not followed by the crew, leading to more detailed safety studies [16].

B. STAR/SID Conflict

A situation which gives rise to low-altitude RAs is the crossing of departure and arrival patterns. As with parallel approaches, these occur in regions under close ATC monitoring but here, the potential for harm is higher. This is due to the aircraft in these situations having opposite intended trajectories rather than ultimately travelling on similar horizontal and vertical trajectories as with parallel approaches.

In Fig. 13 and 14, we can see QXE2144 and SWA3303 near Seattle–Tacoma Airport. With SWA3303 climbing and QXE2144 descending, both aircraft received ‘level off’ RAs to maintain vertical separation until they had better horizontal separation. In this situation, the aircraft would have passed very close to each other without TCAS intervention. Notably, the RA occurs prior to the horizontal crossing.

Similarly, Fig. 15 and 16 show RPA3725 on departure from and AAL2436 on arrival to Dallas–Fort–Worth Airport. Here, the RA occurs during the horizontal crossing. As with the previous example, TCAS issues ‘level off’ RAs here due to the intended vertical and horizontal crossing of the aircraft. These were important to follow as otherwise the aircraft would have lost a considerable amount of separation.

Monitoring the regularity of cases such as these could be useful in identifying regularly conflicting departure and arrival paths, which could be adjusted to reduce the chance of conflicts in the future. Narrow 1000ft separations between STAR and SID procedures at the point they cross is a common cause of false alerts on ATC and TCAS systems, which lead some airports to adapt their procedures with a 2000ft separation between these paths.

C. Top of climb and/or beginning of descent

In Fig. 17 and 18 FIN7HL and AZA1491 cross their paths above Italy. A possible loss of separation seems to have been anticipated by the local ATC[4] who gave clearance to FIN7HL to descend to FL310 and to AZA1491 to climb to FL300, ensuring a conflict-free situation. Climbing and descending rates were interpolated by TCAS systems, yielding RAs to prevent a possible loss of separation. Indeed, TCAS in its current configuration is neither aware of ATC clearances nor does it take into account the altitude setting in the MCP. Recommendations have been issued in the European ATM Master Plan in order to take this setting into account in future ACAS systems.

VIII. Discussion

Collision avoidance systems are a crucial cornerstone of managing modern air traffic and have helped to improve safety in increasingly busy airspaces. However, not much independent research has been done by the scientific community on the inner workings and the efficacy of the system. Recently, Aireon, providers of the first space-based ADS-B receiver system have conducted some preliminary analysis of TCAS data collected with their global satellite constellation [17]. The work shows that it is possible to receive TCAS RAs in space and analyze losses of separation using Aireon’s receiver system. While this proof of concept shows that satellite receivers can be a helpful supporting system, in particular in Oceanic airspace and other non-surveillance regions, the received data is not freely available for independent researchers to work on.

In contrast, besides the presented analysis of typical RA situations and a first look at wider statistics surrounding TCAS, the present work aims to facilitate future research in the area of collision avoidance. With the decoder open

[4]MCP altitude setting is available as part of the Mode S Comm-B standard, in the BDS 4,0 fields. The availability of such messages depends on the ACC and on the configuration of local secondary radars. The usage of such messages is rather consistent across Europe.

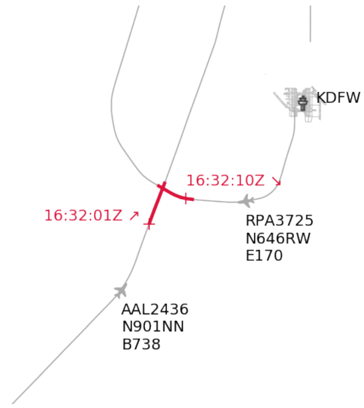

Fig. 15. Flight paths of RPA3725 and AAL2436 around Dallas–Fort–Worth Airport (KDFW) on intersecting departure and arrival trajectories. Parts of path marked in red indicate distance covered during a TCAS RA.

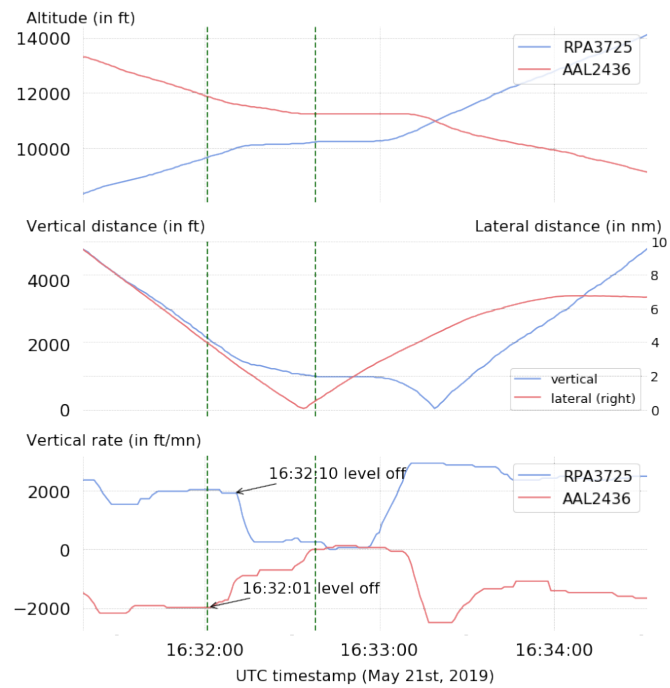

Fig. 16. Altitudes of RPA3725 and AAL2436 along with horizontal and vertical separation between the aircraft during the time period surrounding the RA on departure from/arrival to Dallas–Fort–Worth Airport (KDFW). RA time period is denoted by green vertical lines.

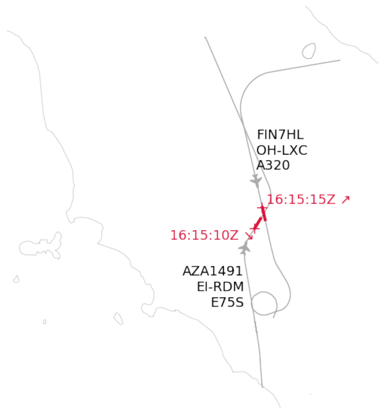

Fig. 17. Flight paths of FIN7HL and AZA1491 above Italy. Parts of path marked in red indicate distance covered during a TCAS RA.

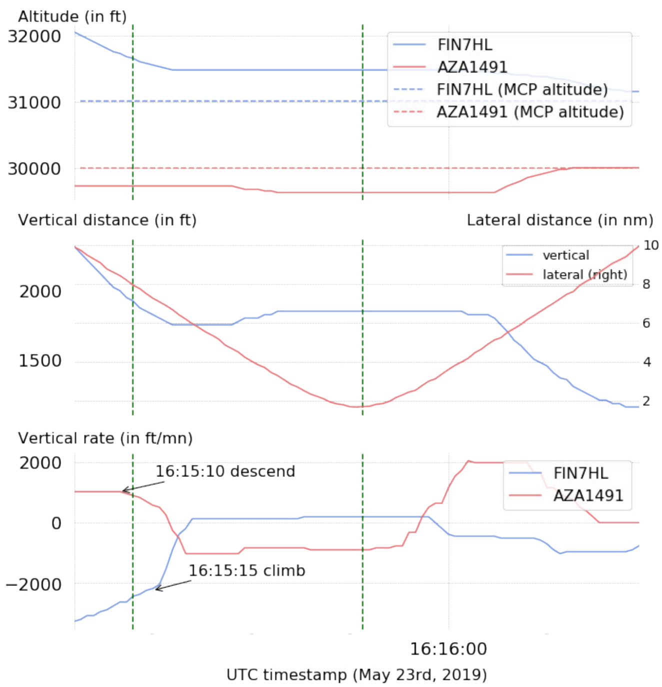

Fig. 18. Altitudes of FIN7HL and AZA1491 along with horizontal and vertical separation between the aircraft during the time period surrounding the RA. RA time period is denoted by green vertical lines. MCP altitude (corresponding to ATC clearance) is denoted by horizontal dashed lines.

sourced and the collected historical TCAS data freely available to researchers through the OpenSky Network, we hope that many others will look more deeply into this crucial and safety-critical area in the future.

IX. Conclusion

In this paper, we have analyzed the current usage characteristics of TCAS, the Traffic Alert and Collision Avoidance System, by using global data from the crowdsourced research network OpenSky. We have gathered statistical data and anecdotal case studies, which provide insights into the use of TCAS worldwide. We have developed an open source decoder for TCAS messages to conduct this research and enable other interested parties to gather their own data. Based on this decoder, the OpenSky Network also offers existing historical data going back to 2016, which can facilitate more detailed TCAS research in the future even for researchers without their own collection sites.

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