

IDENTIFYING COLLISION AVOIDANCE RESOLUTION ADVISORIES AND ANOMALIES IN AIRCRAFT AVIONICS GLOBALLY WITH SPACE-BASED ADS-B DATA OBSERVATIONS

Andy Hoag, Dr. Michael A. Garcia, and John Dolan: Aireon, 1750 Tysons Blvd, Suite 1150, McLean, VA 22102, USA

Phone: +1.703.287.7464, Email: Andrew.Hoag@aireon.com

Presenting Author: Andy Hoag

Abstract

Aireon's nearly complete deployment of 66 payloads on the Iridium NEXT constellation has enabled global surveillance of tens of thousands of aircraft for the first time. Using 1090 MHz Automatic Dependent Surveillance-Broadcast (ADS-B), the Aireon system receives messages broadcast from equipped aircraft. As ADS-B equipage rises and mandates are enacted in regions around the world, observations of anomalies and outliers have increased. Aireon has been closely monitoring and analyzing the data to characterize the outliers in preparation for reporting to governing bodies such as the European Aviation Safety Agency (EASA), EUROCONTROL, the Federal Aviation Administration (FAA), and the International Civil Aviation Organization (ICAO). In addition to these outliers, the inclusion of traffic collision advisory data allows safety hotspots to be outlined.

Non-compliant aircraft are commonly observed in the global ADS-B data set. Examples of non-compliant aircraft include aircraft transponders that do not adhere to the Minimum Operational Performance Standards (MOPS) and the rules outlined in ICAO Annex 10. Position outliers duplicate 24-bit addresses, and invalid aircraft identification data are examples of such observations. The transponder issues are probably not intentional and aircraft operators, Air Navigation Service Providers (ANSPs), Civil Aviation Authorities (CAAs), and ICAO may be unaware of many of the non-compliant transponders due to a lack of data and coverage and reliance on radar. The presence of duplicate 24-bit addresses is a safety concern that can lead to dropped tracks in surveillance systems and missed alerts in TCAS. [1] [2]

In addition to non-compliant aircraft, Aireon has had the opportunity to analyze Traffic Collision Avoidance System (TCAS) Resolution Advisories (RAs) on a global scale using the RA broadcast

message included in version two of the 1090 Extended Squitter ADS-B MOPS. This data can be used to better describe collision risk scenarios and identify areas with frequent RA activity. Some countries independently monitor TCAS via Mode S [3], but Aireon can monitor of TCAS data received via ADS-B messages, including oceanic regions outside of radar coverage. EUROCONTROL's December 2017 ACAS Guide states that there is no European-wide data on the frequency of RA occurrence. [4] The data collected from Aireon may be the first global look at RA occurrences.

ICAO document 9863 notes that monitoring via controller reports is typically mandated by a state, pilot reporting can be used, and data from surveillance is voluntary. [5] A 2009 report concludes that only 48% of climb/descend RAs and 20% of other RAs are reported by pilots. [3] A global monitoring system could assist in filling in the gaps and correlating preventative and corrective TCAS RA events.

This paper outlines examples of non-compliant aircraft from Aireon data, methods of detecting non-compliance, and proposes the implementation of global monitoring and reporting for regulatory agencies. In addition, the paper illustrates examples of preventative and corrective TCAS RAs using Aireon data. The exact date, position, and identity data are redacted for corrective RAs.

I. Resolution Advisories

TCAS is a specific implementation of the ICAO Airborne Collision Avoidance System (ACAS). [6] [7] While TCAS makes use of 1030 MHz and 1090 MHz for interrogation and reply, a copy of any resulting RA information is transmitted in specific ADS-B messages by aircraft equipped with MOPS version two (DO-260B/ED-102A) transponders.. The 1090ES TYPE Code 28, subtype 2 message contains the TCAS Resolution Advisory and the data format is defined per

ICAO Annex 10, Vol IV, § 4.3.8.4.2.2.1. [8] [9] A sample of RA broadcasts received by Aireon over multiple days is illustrated below in Figure 1. Not every point on the map represents a critical event, or even a loss of separation as the algorithms used for collision avoidance can generate unnecessary or nuisance alerts. [7]

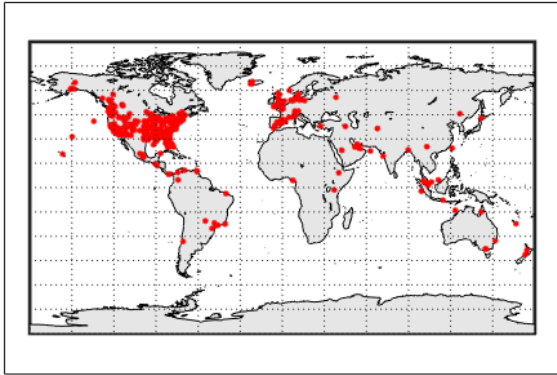


Figure 1: Sample of TCAS RAs (Preventative and Corrective) Based on ADS-B Data Observed by Aireon

The higher density of RA events reported via ADS-B over United States airspace is likely due to the equipage rate of version two transponders (given the January 2020 mandate) as opposed to a reflection of total RA occurrences. [10] Therefore, the measurement of RAs with ADS-B will become more accurate as version two equipage increases. Using Aireon data from August and September 2018, a heat map illustrating the percent of version two (vs. version 0 and version 1) aircraft per tile shows a higher population of version two targets over the United States. This plot is shown in Figure 2 below.

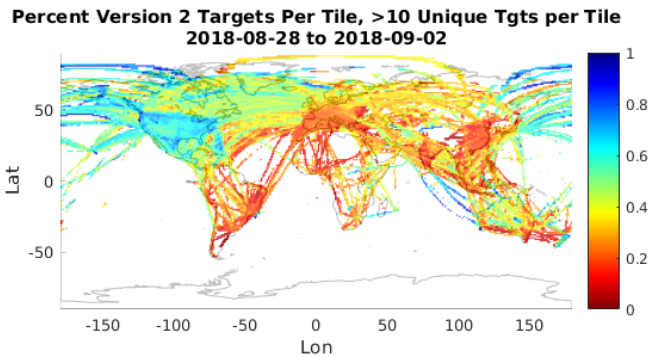


Figure 2: Density of DO-260B (version 2) Aircraft

An RA event observed using Aireon ADS-B data in early 2018 is detailed below in Figure 3 and Figure 4. The two wide-body targets illustrated were flying

over the ocean on the same track in opposite directions and it is unknown if the targets were within radar contact. The first target, flying at 37,700 feet with a ground speed of 520 knots, was in a climb while the second target, flying at 38,000 feet with a ground speed of 427 knots, maintained its flight level. The two targets were separated by less than nine nautical miles with a lateral closure rate of approximately 947 knots, or about 0.26 nautical miles per second as shown at 03:46:07.

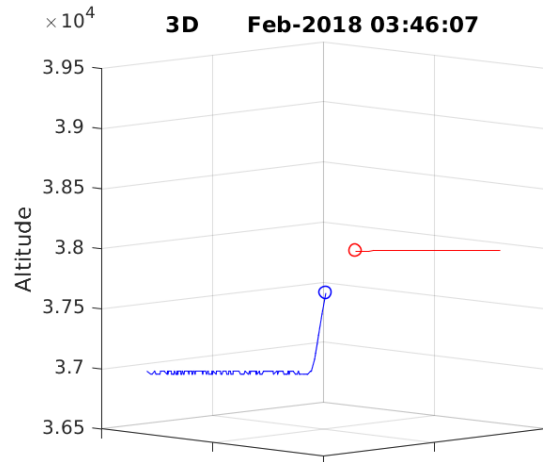
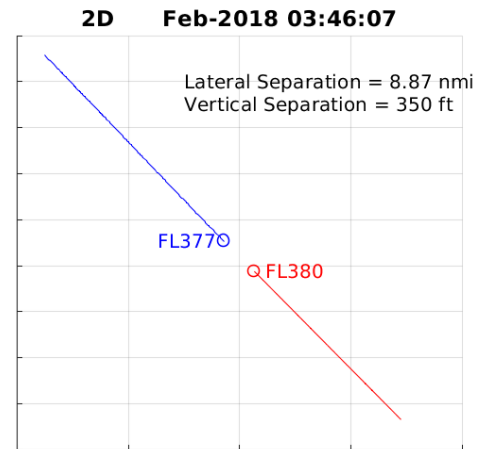


Figure 3: Resolution Advisory , Over Ocean, Before Corrective Action

At 03:46:08, Aireon received an ADS-B RA broadcast report from the first target (in blue) in the above example. Table 1 details the contents of the RA message which indicates that the aircraft should descend. The target descended at 1665 feet per minute and the second target climbed at 2880 feet per minute in response to the RA.

Table 1: Example 1 RA Broadcast Received from the First Target

Subfield	Bits Set [9]
ARA	-Only one threat -RA is corrective -Downward sense RA has been generated -RA is not increased rate -RA is not a sense reversal -RA is not altitude crossing -RA is positive
RAC	-Do not pass above
RAT	-ACAS is currently generating the RA indicated in the ARA subfield
MTE	-The resolution logic is processing one threat
TTI	-TID contains a Mode S transponder address
TID	-24-bit address of the second target

This reaction by both aircraft resulted in separation to satisfy the instructions from the TCAS RA, shown in Figure 4.

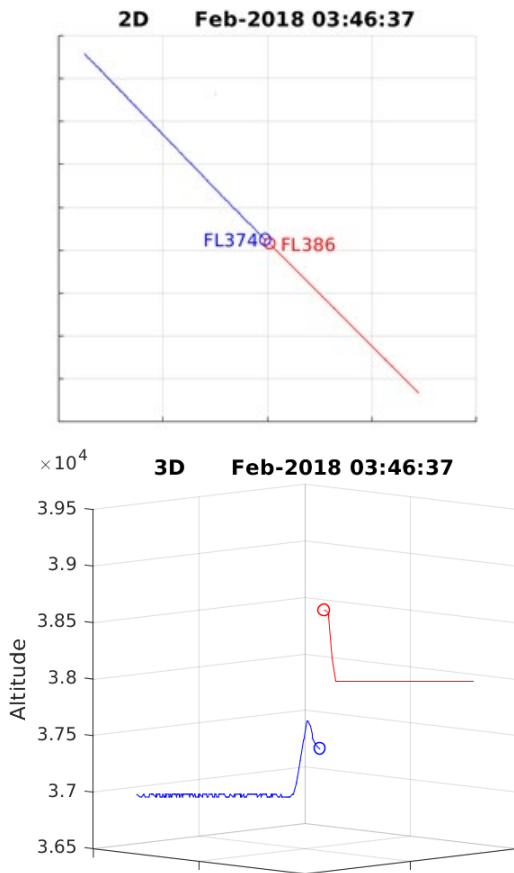


Figure 4: Resolution Advisory, Over Ocean, After Corrective Action (30 seconds after Figure 3)

Encountering high-altitude RA events is assumed to be uncommon. Using terrestrial surveillance data, Olson and Olszta reported that 97.4% of RAs in the

United States occur below 18,000 feet and 86% below 10,000 feet. [11] Between 28 August 2018 and 3 September 2018, Aireon observed ADS-B RA reports from 462 unique targets. Though the sample set is relatively small compared to other TCAS studies, Aireon found that 78% of RAs occur below 10,000 feet. A histogram of altitude per RA is shown in Figure 5.

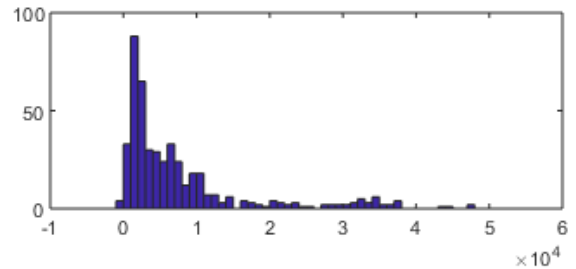


Figure 5: RA Distribution by Altitude

A more common RA example is one occurring in the approach and departure areas in the airspace surrounding a busy airport. Such an event from summer 2018 was located and is illustrated in Figure 6 and Figure 7. The two targets in were both equipped with ADS-B version two, and each reported corrective RA reports via ADS-B.

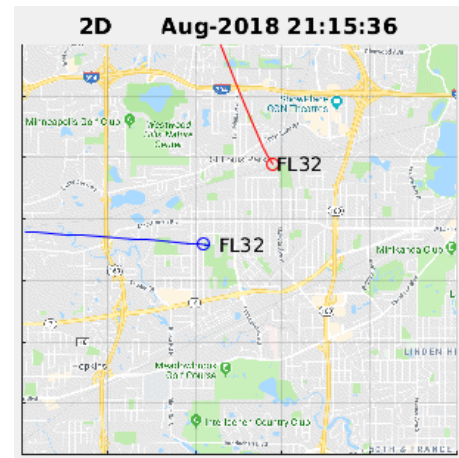


Figure 6: Resolution Advisory, on Approach

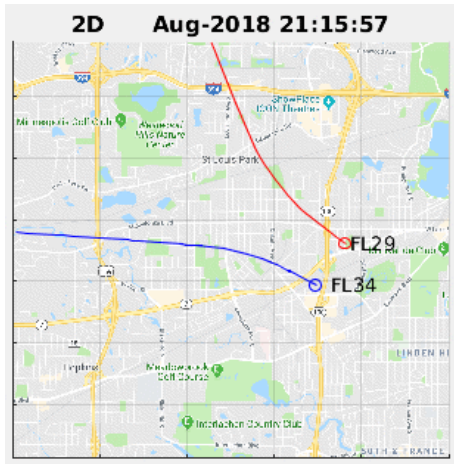


Figure 7: Resolution Advisory, on Approach (21 seconds after Figure 6)

II. Mode S / 24-Bit ICAO Addresses

Over a five-day period, from 28 August 2018 to 1 September 2018, Aireon observed 47,684 individual 24-bit addresses. A small subset of the addresses are duplicates, a condition when the same address is broadcast by two different aircraft. EUROCONTROL states that the presence of duplicate 24-bit addresses can jeopardize the safety of aircraft and must be avoided at all times. [1] These duplicates not only affect ADS-B, but also affect radar and TCAS and can cause missed TCAS RAs. [2]

Common duplicate addresses include 0x000001, 0x123456, and 0xA00000. A listing of unique aircraft identifications (ACIDs) per duplicate is detailed below in Table 2.

Table 2: Unique ACIDs for Common Duplicate Addresses

Date Range	Common Duplicate 24-bit ICAO Address	Unique ACIDs Observed
2018-08-28 to 2018-09-01	0x000001	32
	0x123456	23
	0xA00000	14

The list of common duplicates is small and spread throughout the world. Figure 8 illustrates the locations of 0x000001 targets based on Compact Position Reporting (CPR) decoding.

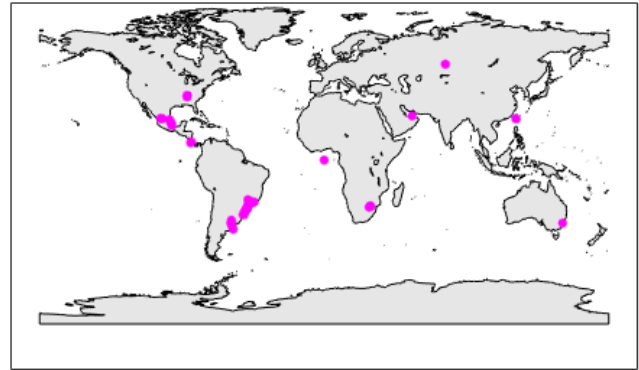


Figure 8: CPR Decodes of 0x000001

It is assumed that the common duplicates are probably unintentional and are potentially caused by human error in transponder configuration. It is not known if regulators are aware. ANSPs and regulatory agencies could benefit from periodic updates on such observations to reduce occurrences.

III. Aircraft Identification

The intent of the aircraft ACID or flight identification field in ADS-B is to provide the filed flight plan ID or the registration/tail number. [9] Over a five-day period from 28 August 2018 to 1 September 2018, Aireon observed 146,374 unique ACIDs. This number is more than three times the number of unique 24-bit addresses as airlines re-use airframes for multiple flights. Many of the individual ACIDs follow the filed flight plan, while others report registration. A sample of several airlines is outlined below in Table 3. The search format used to populate the table was: three-letter ICAO airline designator followed by at least one number.

Table 3: Sample of Valid Unique ACIDs Observed by Airline between 2018-08-28 and 2018-09-01

Airline with Three-Letter ICAO Designator	Valid Unique ACIDs Observed from ADS-B
AAL – American Airlines	2390
DAL – Delta Air Lines	2318
CSN – China Southern	2127
UAL – United Airlines	1826
DLH – Lufthansa	1454
AFR – Air France	953
BAW – British Airways	926

In addition to the expected ACID formats, several anomalous strings were also found in the datasets. During the five-day analysis period, 38 ACIDs contained the string TEST or TST. Examples include

AALTEST, ATCTEST, ADSBTEST, TEST1234, TEST222, TEST333, and RU7TEST1. Other suspected test targets include EMMATT, GPSMON T, INDRAMKT, and multiple variations of PARROT.

In addition to the test targets, there were several instances of aircraft reporting ACIDs that did not contain tail number or flight plan, which does not align with ICAO standards. Examples include HITHERE, HELLOATC, GOODMRNG, GOJUMP1, FLIGHTID, and CUBGIRL. Many of these reports occur on the ground, likely out of range of Mode S radars. An example of the HITHERE report is illustrated in Figure 9.

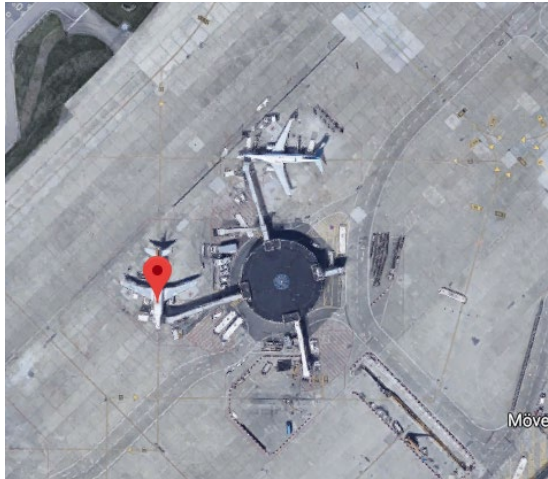


Figure 9: Position of HITHERE Aircraft

Other aircraft have reported invalid ACIDs while airborne. Based on the 24-bit address, the HELLOATC target was found to be operated by a regional airline. [12] A plot of the HELLOATC flight is shown in Figure 10.

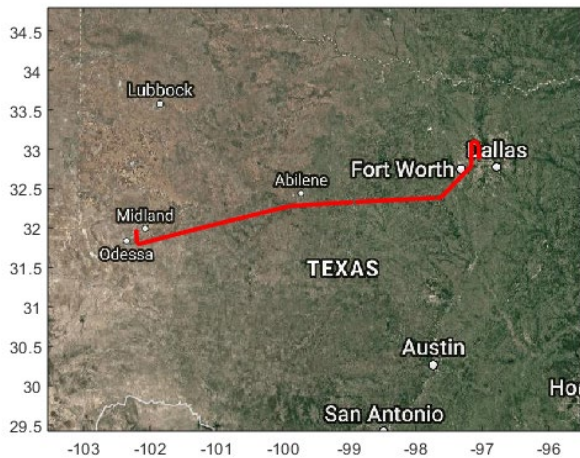


Figure 10: Plot of the HELLOATC Flight

During the five-day analysis period, 1,346 ACIDs contained only numbers or started with at least two digits. This format does not follow the ICAO three-letter designator or registration based on nationality mark. [13] It is suggested that most of the 1,346 are invalid and require enforcement activities. While this is more of a non-compliance than an anomaly, enforcement activity from ICAO, ANSPs, and regulators would help to bring the aircraft into acceptable performance.

In January 2018, Aireon reported to RTCA 731 unique aircraft broadcasting the same invalid character (0b101110) in the first position of the ACID. [14] This invalid character is not defined in ICAO Annex 10 or in the MOPS. [9] [8] The format most frequently observed is a single instance of the invalid character followed by the aircraft registration. This anomaly tends to occur when the aircraft is operating without a flight plan – on the surface or in the air. This condition still happens today, and the observation count is up to 909 aircraft over a ten-day period from August 2018 to September 2018. Using the non-compliant ACIDs, a table of observations based on country of registration was created in Table 4.

Table 4: Invalid Character Observations per Country of Registration – Sample

Country of Registration	Observations of Invalid Character 0b101110
United Arab Emirates (A6)	21
China (B)	183
Germany (D)	16
United States (N)	182
Chile (CC)	5
Morocco (CN)	2
France (F)	7
Thailand (HS)	18

Many of the observed registrations are sequential, suggesting that the affected aircraft are part of a fleet. The Federal Aviation Administration (FAA) public registry [12] confirmed that a sample of 30 the US-registered aircraft all share the same airframe manufacturer which suggests common avionics.

IV. Position Anomalies

Aireon has observed several examples of aircraft reporting invalid position. Position errors may occur at the GNSS receiver, the interface to the transponder, or in the transponder itself. Many erroneous position

reports can be removed by using the range check outlined in the MOPS, or through timing calculations such as time difference of arrival (TDOA). [8] For aircraft that consistently report erroneous data, using this solution to remove invalid reports can mask underlying issues.

An example of an aircraft continuously reporting invalid position is illustrated below in Figure 11. The aircraft follows an improbable trail along the prime meridian and consistently reports similar erroneous position each time it is in flight.

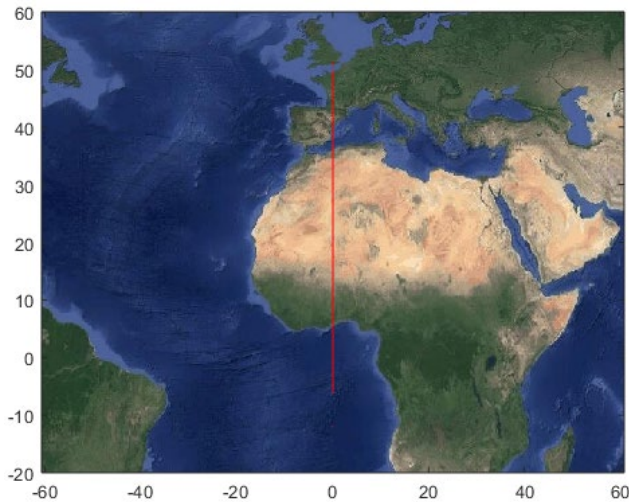


Figure 11: Aircraft Reporting an Improbable Trip Along the Prime Meridian

The operator of the aircraft may not be aware of the issues as the example aircraft has exhibited this behavior for months.

V. Future Applications

RAs should be monitored via surveillance to satisfy ICAO requirements as many pilots do not make reports. [3] In the past, RA monitoring would require additional ground-based infrastructure. The advent of space-based surveillance allows monitoring to occur without significant investment in new equipment. These events are also best observed over whole flight paths rather than confined to separate airspaces.

The anomaly and non-compliance observations outlined in this paper are not specific to ADS-B. The same issues also affect Mode S radars, surface surveillance, wide area multilateration and air-to-air applications including ACAS/TCAS. A global data set of ADS-B data can be used to help ICAO, ANSPs,

airlines, avionics manufacturers, and regulatory bodies actively support alignment to standards and regulations.

VI. Conclusion

The use of Aireon's global ADS-B dataset has uniquely enabled the compilation of both RAs and anomaly information into a single view and analysis context. Civil cooperative surveillance requires all actors to adhere to a set of MASPS and MOPS, ensuring safe and seamless operations and data exchange. Aireon is an active part of the aviation community and plans to offer additional services and applications in support of achieving higher levels of global interoperability.

VII. Acknowledgements

The authors would like to thank Vinny Capezzuto and Don Thoma for their technical review and contributions to this paper. The authors would also like to thank Aireon interns Patrick Byerly and Noah Grant for their work related to other aircraft observations that may be outlined in a future paper. The authors would also like to thank NAV Canada, Iridium, ENAV, NATS, IAA, and Naviar for their continued support of the Aireon program.

VIII. References

- 1] EUROCONTROL, "Mode S," [Online]. Available: <http://www.eurocontrol.int/articles/mode-s>.
- 2] EUROCONTROL, "Transponder failure," *NETALERT - the Safety Nets newsletter*, pp. 6-7, May 2014.
- 3] C. Avenau, B. Hasquenoph and B. Raynaud, "Operational investigation of TCAS reports by pilots," [Online]. Available: <https://www.eurocontrol.int/sites/default/files/content/documents/nm/safety/ACAS/safety-acas-report-operational-investigation-tcas-reports-by-pilots-20091005.pdf>.
- 4] EUROCONTROL, "ACAS Guide Airborne Collision Avoidance," December 2017. [Online]. Available: <https://www.eurocontrol.int/sites/default/files/c>

ontent/documents/nm/safety/ACAS/safety-acas-II-guide.pdf. [Accessed 14 June 2018].

5] International Civil Aviation Organization (ICAO), "Airborne Collision Avoidance System (ACAS) Manual," 2006.

6] Federal Aviation Administration, "Introduction to TCAS II Version 7.1," [Online]. Available: https://www.faa.gov/documentLibrary/media/Advisory_Circular/TCAS%20II%20V7.1%20Intro%20booklet.pdf.

7] EUROCONTROL, "Overview of ACAS II / TCAS II," 2009. [Online]. Available: http://e-atpl.net/pdf/ACAS_overview_Jan09.pdf.

8] RTCA, Inc., DO-260B Minimum Operational Performance Standards (MOPS) for 1090 MHz Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Services - Broadcast (TIS-B) with Corrigendum 1, 2009.

9] International Civil Aviation Organization (ICAO), *Annex 10 to the Convention on International Aviation, Aeronautical Communications, Volume IV Surveillance and Collision Avoidance Systems*, 2014.

10] United States Government, "Electronic Code of Federal Regulations, Title 14, Chapter I, Subchapter F, Part 91 - General Operating and

Flight Rules," [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?node=14:2.0.1.3.10#se14.2.91_1225.

11] W. A. Olson and J. E. Olszta, "TCAS Operational Performance Assessment in the U.S. National Airspace," in *29th Digital Avionics Systems Conference*, 2010.

12] Federal Aviation Administration, "FAA Registry," [Online]. Available: https://registry.faa.gov/aircraftinquiry/NNum_Rresults.aspx.

13] ICAO, "Aircraft Nationality Marks and Common Marks," [Online]. Available: https://www.icao.int/safety/airnavigation/NationalityMarks/alpha_state.pdf.

14] A. Hoag, M. Garcia and J. Dolan, "Clarification on use of defined characters in aircraft identification," in *Joint Session for ATCRBS / Mode S Transponder MOPS, ADS-B 1090 Extended Squitter MOPS; CSC Meeting #8*, Miami, 2018.

2018 Enhanced Solutions for Aircraft and Vehicle Surveillance (ESAVS) Applications Conference

October 17-19, 2018