Using Automatic Dependent Surveillance-Broadcast Data for Monitoring Aircraft Altimetry System Error

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Altimetry System Error (ASE) is a measure of the height-keeping performance of an aircraft. In airspace where the Reduced Vertical Separation Minimum (RVSM) is applied, the importance of accurate aircraft height-keeping is magnified. ASE is not detectible in routine operations; specialized measurement equipment is necessary to independently measure the errors. To be eligible for RVSM operations, operators must adhere to the height-keeping performance monitoring requirements established for the airspace in which operations are to be conducted. The Federal Aviation Administration (FAA) developed a process to monitor the height-keeping performance of aircraft for RVSM operations. The International Civil Aviation Organization (ICAO) has established long-term minimum monitoring requirements to be used by the regions where the RVSM is implemented which go into effect in November 2010. This paper progresses the work which considers the role of a Next Generation Air Transportation System (NextGen) technology, Automatic Dependent Surveillance–Broadcast (ADS-B), to monitor the height-keeping performance of aircraft. This paper contains results from test flights conducted at the FAA Technical Center to compare aircraft geometric height obtained from three sources; ADS-B, EGMU, and an onboard independent GPS reference receiver. In addition, this paper presents initial results from ADS-B data collected from real airspace operations. The ADS-B data made available for this work result from a cooperative research agreement between the FAA and Airservices Australia. The results of this study will be used to determine the quality control processes needed for monitoring aircraft ASE using ADS-B geometric height data.

I. Introduction

The Federal Aviation Administration (FAA) introduced the Reduced Vertical Separation Minimum (RVSM) between flight level 290 and 410, inclusive, in the domestic United States National Airspace System (NAS) on January 20, 2005. This change reduced the vertical separation between aircraft from 2000ft to 1000ft. This separation reduction followed successful implementations of RVSM in other airspaces throughout the world, including the North Atlantic and Pacific Oceanic airspace along with European domestic airspace. With each implementation, the RVSM was introduced under guidance provided by the International Civil Aviation Organization’s (ICAO’s) Manual on the implementation of a 300 m (1,000 ft) Vertical Separation Minimum between FL290 FL410 Inclusive, ICAO Doc 9574 (Ref. 1). The ICAO is a specialized agency of the United Nations (UN), responsible for ensuring the safe, efficient and orderly evolution of international civil aviation. Ref. 1 contains requirements for monitoring of aircraft altimetry system error (ASE). ASE is defined in Ref. 1 as the difference between the altitude indicated by the altimeter display, assuming a correct altimeter barometric setting, and the pressure altitude corresponding to the undisturbed ambient pressure.1

ASE is a measure of the height-keeping performance of an aircraft. In airspace where reduced vertical separation standards are applied, the importance of accurate aircraft height-keeping performance is magnified. Aircraft use a barometric altimeter to determine height and follow common pressure levels in RVSM airspace. The errors in the aircraft altimetry sensing systems are not apparent during routine operations as the altimeter displays to the aircrew and air traffic services (ATS) a flight level which contains the ASE. Due to the existence of aircraft ASE, the observed flight level by the pilot and ATS is different than the actual height of the aircraft. Aircraft undergo routine maintenance which includes recalibration of the altimetry systems. The altimetry system utilizes

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parts that can wear over time (e.g. the pitot-static probe); can be damaged (e.g. skin flexing/deformation during operations); and can be effected by modifications made to the airframe (e.g. the application of paint or mounting of accessories in the vicinity of the static pressure port). These activities can affect the aircraft’s altimetry system in a negative way, producing a significant error in true height. Other factors from normal operations of high-speed flight such as aerodynamic loading and exposure to ranges of temperature, moisture and contaminants, are also capable of producing significant variation in the sensed pressure of the altimetry system. Aircraft ASE can vary over the population of operational aircraft of the same type and, for each specific airframe, the ASE can vary with time in service. Since the ASE is not detectable in routine operations; specialized measurement equipment is necessary to independently measure the errors. If an aircraft is unable to maintain its desired altitude relative to others, it poses a greater threat to the other aircraft in the system. Therefore, the ICAO developed standards that individual aircraft and aircraft groups must meet in order to operate in RVSM airspace. An individual aircraft must maintain an airworthiness approval, which states that the aircraft can maintain an ASE value of 245 ft or less. An aircraft type group, which consists of airframes that belong to a specified aircraft type group, must possess a mean ASE value less than 80 ft in magnitude, and the absolute value of the ASE mean plus three standard deviations must be less than 245 ft.

The ICAO requires its member States to establish a safety program in order to achieve an acceptable level of safety in the provision of ATS. In the specific case of the implementation and ongoing operation of RVSM, ICAO requires that an aircraft height-keeping performance monitoring program be established for all airspace where a RVSM of 1,000 ft is applied for aircraft operating within Flight Level (FL) 290 and FL 410 inclusive, in order to ensure that the implementation and continued application of the RVSM meets the safety objectives. In addition, ICAO has established forthcoming long-term height monitoring requirements which will be detailed in amendments to the ICAO Annex 6 – Operation of Aircraft (Ref. 3). The amendments to Ref. 3 provide guidance on the global RVSM long-term monitoring requirements which become effective in November 2010. In order to ensure the continued safe-use of the RVSM, aircraft operators and ICAO member States must adhere to these new long-term monitoring requirements.

Existing methods used to estimate aircraft ASE are described in Ref. 4 and include both ground-based and portable systems. Ref. 4 provides an initial examination into the use of Automatic Dependent Surveillance-Broadcast (ADS-B) for estimating aircraft ASE. The study contained in this paper progresses the work contained Ref. 4 and examines the validity of the ADS-B data under uncontrolled conditions.

### II. Background

ASE is a measure of the altimetry system’s ability to correctly evaluate and convert ambient static pressure to the height corresponding to the ICAO Standard Atmosphere. Flight Technical Error (FTE) is the difference between the altitude indicated by the altimeter display being used to control the aircraft and the assigned altitude/flight level. Figure 1 shows the relationship between these two types of errors along with the Assigned Altitude Deviations (AAD). AAD is the difference between the transponded Mode C altitude and the assigned altitude/flight level.

The new generation of altimeters provides very accurate conversions from the sensed static-pressure to height. However, the measurement of static-pressure remains sensitive to airflow in the vicinity of the sensor. The airflow may be affected by distortions of the aircraft skin near the static-pressure probe or obstructions to the static-pressure input. Additionally, the airflow varies throughout the flight envelope and dynamic adjustments are required in order to properly sense the static pressure. These types of errors are hidden from both the pilot and the air-traffic-controller. That is, they have no instrument to gauge when the pressure sensed

![Figure 1. Components of Total Vertical Error (TVE)](image)

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The existing methods to estimate aircraft ASE include use of a portable device, the Enhanced GPS Measurement Unit (EGMU) and ground-based systems located in Europe, the United Kingdom and the United States. The European and United Kingdom’s ground-based systems are called Height Monitoring Units (HMUs) and the United States ground-based systems are called Aircraft Geometric Height Measurement Elements (AGHMEs). The differences among the various existing monitoring systems are described in Ref. 4.

ADS-B allows equipped aircraft to automatically broadcast their position, velocity, and other information with each other and with air traffic controllers. ADS-B equipped aircraft use an on-board Global Positioning System (GPS) receiver to determine their position; this time-stamped information is then broadcast along with other aircraft information to all ADS-B capable aircraft and to ADS-B ground or satellite communications receivers. These receivers then forward the information to Air Traffic Control (ATC) centers. The ADS-B reports includes aircraft geometric height, which is a key component in the ASE estimation process.

The geometric height obtained from the EGMU is differentially corrected prior to the ASE calculation. This means that much of the position errors are removed from the GPS-derived geometric height with further processing. During development of the EGMU, the FAA Technical Center determined that aircraft geometric height produced using EGMU-collected pseudo-ranges then improved using differential correction was of sufficient accuracy to support adequate estimation of TVE, AAD and ASE.

The GPS-derived geometric height contained in the ADS-B message is not differentially corrected. It is not possible to post-process these geometric heights because the information needed to correct the errors is not included in the ADS-B messages. Some conditions have changed since the initial determination of suitability of uncorrected GPS pseudo-ranges. First, aircraft grade GPS receivers have improved markedly and being capable of tracking more satellites simultaneously. Additionally, the Selective Availability (SA) feature of the GPS system has been completely disabled to the point where non-precision approaches can be attempted with its course guidance. These changes in conditions mean that better accuracy can be expected in the geometric height determined from the modern receivers. Some modern receivers have the ability to use the Wide Area Augmentation System (WAAS). WAAS is an air navigation aid developed by the FAA with the goal of improving the GPS position accuracy, integrity, and availability. WAAS covers almost all of the NAS collecting data from numerous Wide Area Reference Stations (WRS) and forwarding them to the WAAS Master Station (WMS). Augmentation messages are created at the WMS which allows GPS receivers to remove errors in the GPS signal. However, it is not possible to determine whether WAAS corrections were applied to ADS-B aircraft geometric height data unless it is known that the airframe is equipped with WAAS – this information is typically not available.

III. Objective

The FAA is currently in the process on increasing the ADS-B infrastructure in the US. Many other countries are also initiating programs to include ADS-B as components of their Air Traffic Service Systems. Aircraft geometric height data, which is included in the ADS-B messages, is an important component in the calculation of ASE. The existence of the geometric height data make it possible for ASE to be estimated from ADS-B reports. The forthcoming ICAO long-term monitoring requirements state that aircraft which operate in RVSM airspace must undergo periodic monitoring for height-keeping performance. These forthcoming ICAO requirements will apply to all aircraft operators in RVSM airspace. The purpose of this study is to progress the work contained in Ref. 4 and determine whether the geometric height information contained in the ADS-B data is sufficiently accurate to estimate aircraft ASE under uncontrolled conditions.

The test flights conducted for the study contained in Ref. 4 used data from GPS receivers which were enabled with WAAS corrections. The use of WAAS is not mandatory for airspace operations; therefore data from GPS systems without WAAS corrections applied should be examined to determine whether data from ADS-B systems without WAAS are sufficient for estimating aircraft ASE. This paper contains results of additional test flights conducted to examine the estimate of aircraft ASE using geometric height data with WAAS corrections disabled.

In addition, the FAA and Airservices Australia have established a cooperative agreement to further the investigation into the use of ADS-B data for estimating aircraft ASE. Australia has an extensive network of ADS-B ground stations and an aggressive mandate for all aircraft operations to use ADS-B by 2013. As part of this cooperative research agreement, the FAA is modifying existing ASE estimation processes to make use of large amounts of ADS-B geometric height data for producing estimates of aircraft ASE. This study will examine the ASE estimates resulting from this cooperative effort. The main differences between the study contained in this paper and Ref. 4 are the variable environmental conditions, and the variety of airframes and operators evaluated. The objective
for this paper is to determine whether additional processing and quality control procedures are needed to utilize the geometric heights recorded in the ADS-B data for these data to be used in the estimation of aircraft ASE.

IV. Results from Test Flights

Details and results of the test flights conducted to initially examine the use of ADS-B geometric height data for estimating aircraft ASE were presented in Ref. 4. One of the conclusions presented in Ref. 4 stated that there was an apparent 25 ft bias in the aircraft geometric height data obtained from the 1090 Extended Squitter (ES) system – this conclusion has now been shown to be false. Shortly after the AIAA GNC 2008 conference, an error in the raw binary ADS-B data processing was uncovered and has since been corrected. This processing error was determined to be the root cause of the observed 25 ft bias in the data.

These initial test flights were conducted with the WAAS corrections enabled for both the Universal Access Transceiver (UAT) and the 1090 ES onboard receivers. Experts from the FAA’s ADS-B surveillance team at the FAA Technical Center indicated that all UAT systems use WAAS corrected data. Therefore, based on the results presented in Ref. 4, the aircraft geometric height data obtained from aircraft equipped with UAT systems are sufficient for estimating aircraft ASE. It was not possible to disable the WAAS corrections on the research aircraft’s UAT receiver for additional test flights.

However, WAAS corrections may or may not be applied in a 1090 ES system. The resulting aircraft geometric height data from a 1090 ES system might be different depending on whether or not WAAS corrections were applied. Therefore, additional test flights were conducted by the FAA Technical Center with the WAAS corrections disabled on the 1090 ES system to determine whether the ADS-B aircraft geometric height obtained from 1090 ES systems with and without WAAS corrections are suitable for estimating aircraft ASE. According to the FAA Technical Center WAAS experts, it is more likely that aircraft operating within RVSM flight levels would be equipped with 1090 ES systems and not UAT systems. These additional test flights were conducted using the same research aircraft, N47, a Bombardier BD-700-1A11 aircraft. This aircraft is equipped with two GPS antenna on top of the fuselage. The WAAS corrections were enabled on the GPS receiver for the UAT system. The WAAS corrections were disabled on the GPS receiver for the 1090 ES system. Both of the GPS receivers, for the UAT and 1090 ES systems, met the criteria for Technical Standards Order (TSO) C145/146.

A. Additional Test Flight Methodology and Results

The treatment of the GPS-derived geometric height is different for each of the ADS-B systems involved – UAT and 1090 ES. The different treatment affects the accuracy and the variability of the resultant data received on the ground. The UAT system rounds the geometric altitude to the nearest 25 ft increment then a transmitter contained in the system sends the geometric altitude and other information to a ground receiver located at the FAA Technical Center. The 1090 ES system collects the pressure altitude along with the difference between the geometric altitude and the pressure altitude. Prior to sending the data to the ground receiver each of these values is rounded to the nearest 25 ft increment. The 1090 ES system uses the aircraft’s Mode S transponder to send the data to a ground receiver located at the FAA Technical Center. The time field in both the 1090 ES and UAT data is in Coordinated Universal Time (UTC). The geometric altitude is reported in feet. The aircraft geometric height data obtained from both ADS-B sources are quantized to 25 ft

Data observed from the aircraft’s independent GPS receiver is referred to as truth data. The geometric heights contained in the truth data are obtained from an independent Ashtech Inc. GPS receiver. The truth data are post processed using Novatel’s software called GrafNav/GrafNet version 6.03. This post processing procedure improves the accuracy of the data by using information collected at various ground stations. The ground stations are arranged throughout the local region and their positions are known, allowing corrections to be determined that are subsequently applied during post-processing. The time field in the truth data is in GPS time (14-second offset from UTC at the time of data collection, since 1 January 2009 GPS to UTC offset is 15 seconds'); the geometric altitude is measured in meters with precision to the ten thousandth of a meter. This system is a recognized position reference.

In order to determine if the geometric heights contained in the ADS-B data are suitable for the estimation of ASE, a comparison is made between the geometric heights from both sources of ADS-B data with the truth data. With the truth data considered absolute reference, this comparison is sufficient in determining if the ADS-B data can be used to estimate aircraft ASE because the geometric heights are a direct input to the process which will compute ASE values and will be treated in the same manner regardless of the source of the data.
It is noted that all the test flights, including the WAAS disabled and WAAS enabled test flights, were conducted under stable conditions. The same airframe, flight path, and similar weather conditions were present for all test flights. In addition, the test flights took place in the mid-latitude region of the northern hemisphere during the solar minimum, or the start of solar cycle 24.\cite{10,11} The solar minimum is the lowest point of the sun's 11-year average activity cycle\cite{10,11} During this time, the rate of solar storms, solar flares, and sun spots is expected to be low. Therefore, any disturbance to the onboard GPS system caused by solar activity is expected to be minimal.

The additional test flights were conducted in the same manner as those described in Ref. 4. Aircraft geometric height data were collected from a total of 10 level flight segments from the test flights.

Results from these test flights, with the WAAS corrections disabled are shown in Figure 2. The box plots in Figure 2 show the data ranges for each source. The horizontal bars above and below the boxes are the maximum and minimum values of the data sets, respectively. The bottom and top of each red box is the lower and upper quartile, respectively. The distance between the lower and upper quartile, the inter-quartile range, provides a measure of the spread of the distribution. Quartiles are defined as the point where the data is divided into four equal parts, meaning that there are an equal number of data points between each quartile. The white line in the center of the red box is the median of the data. Figure 2 shows the data range observed from the two sources are different.

Figure 2 shows the geometric height data range observed from the UAT system is much smaller than that of the 1090 ES system. The geometric height data range observed from the UAT system and the 1090 ES system without WAAS corrections was 5.238 ft and 16.604 ft, respectively. The performances of the systems used to monitor aircraft height-keeping performance have an overall known error of 35 ft. The items that contribute to the overall known error include internal elements, specific to the monitoring system itself, and external elements, such as the meteorological data. An Analysis of Variance (ANOVA) test was used to test for differences among the two samples. In this study, comparisons were made between the differences between each of the data sources and the truth data. Each level flight segment of the test flights represents one replication. The null hypothesis for this test is that the mean differences in geometric heights from both the WAAS disabled and WAAS enabled systems when compared to the truth data are equal. The null hypothesis is tested at a 95% confidence level. The ANOVA test results show that at a 95 percent confidence level the null hypothesis can not be rejected. The results of this test indicate the means of the 1090 ES without WAAS corrections and the UAT with WAAS corrections are not significantly different. All of the data comparisons used in the test came from the same test flights. It was not possible to collect both WAAS disabled and WAAS enabled data from the 1090 ES system. However, the initial test flights presented in Ref. 4 concluded that with one fewer rounding error than the 1090 ES system, the UAT system produces slightly more accurate results. Therefore, the successful comparisons with the UAT system are enough to demonstrate that the WAAS disabled, or aircraft geometric height data obtained from a system without WAAS corrections is sufficient for estimating aircraft ASE.

![Figure 2. Box Plots of the 1090 ES and UAT Aircraft Geometric Height Differences from Truth Data for Test Flights with WAAS Corrections Disabled (1090ES) and Enabled (UAT)](image-url)
A. ADS-B Data Source in the US

The FAA is transforming the current ground-based radar ATC system to a satellite-based system using ADS-B to improve the safety, efficiency, and capacity of the United States NAS. ADS-B is an important component of the Next Generation Air Transportation System (NextGen) as it will enable the NAS to accommodate growth expected from future demand. The NAS deployment plan for ADS-B coverage by 2013 is presented in Figure 3, this figure was obtained from the website listed as Ref. 12. If the use of ADS-B data obtained from normal aircraft operations proves to be suitable for monitoring aircraft ASE, the FAA Technical Center can make use of the available ADS-B data in the future for monitoring aircraft ASE in the US. This capability would add to our already existing AGHME ground-based monitoring systems. The current locations of the AGHME ground-based systems are shown in Figure 4. Prior to the completion of the ADS-B deployment and the availability of ADS-B data in the US, the FAA is making use of ADS-B data obtained from normal operations outside of the US to continue the work in determining the use of ADS-B data for estimating aircraft ASE.

B. Meteorological Data

Meteorological data, needed to determine the geometric height of the assigned flight level coincident with the aircraft ADS-B reports in time and location, are obtained from the US National Oceanic and Atmospheric Administration (NOAA). These data come from basic radiosonde information, satellites, and ground measurement stations. There are four meteorological files containing the temperature estimates at different milibar levels to model the atmosphere at 0000, 0600, 1200, and 1800 UTC. The data at milibar levels 100, 150, 200, 250, 300, 400, 500, 700, 850, and 1000 mbar are provided in the files. The location grid provided is 1.25 degrees latitude by 1.25 degrees longitude for the world. The files provided for the 0000 UTC and 1200 UTC times are based on actual data for the six-hour interval. The files provided for the 0600 UTC and 1800 UTC times are six-hour forecast data.
C. ADS-B Data Source from outside the US

The cooperative research undertaken by the FAA and Airservices Australia began with an initial 9 day sample of ADS-B data collected from seven ground stations spanning the Australian continent. Operations within FL 290 and FL 410 are included for possible ASE monitoring in this work. The ADS-B reports contain the aircraft identification, position, time, Mode S altitude, geometric altitude, and ADS-B ground station identification. The time field in the ADS-B data is in UTC. The geometric altitude is reported in feet. The aircraft geometric height data from ADS-B is quantized to 25 ft. The Mode S altitude, which is equivalent to the aircraft’s altimetry reading, is also quantized to 25 ft. Each ADS-B report also includes a quality factor called Navigational Uncertainty Category (NUC). The NUC is typically derived from the Horizontal Protection Limit (HPL) provided by the GPS receiver (Ref. 13). Airservices Australia’s ATC System only considers ADS-B data “good” and displays ADS-B data to controllers when the NUC value is above a threshold (currently set to 4). According to Ref. 13, if NUC does not reach this threshold, the ADS-B data is not displayed to ATC and the ADS-B service is disrupted to that aircraft. ASE estimates were produced for aircraft which are approved for ADS-B operations in Australia and had acceptable NUC value (greater than or equal to 5) in the available ADS-B reports.

VI. Methodology

The FAA-developed ASE software used to estimate aircraft ASE with the portable EGMU system was modified to provide estimates of aircraft ASE from the large amount of data obtained from the ADS-B ground stations in Australia. The ASE software was developed as a post-processing procedure which requires aircraft geometric height data, actual flight level (altimetry reading) data, intended flight level for the flight segment and an independent source for meteorological data. Prior to producing estimates of aircraft ASE, the ADS-B data were reformatted and preprocessed to remove unnecessary data fields. The ASE processing begins with the identification of unique straight and level flight segments for each flight observed in the data. A straight and level flight segment is defined by a constant flight level (altimetry reading – Mode S) and without turns. Each straight and level flight segment is considered to be an independent observation. It is possible for the same flight/aircraft operation to have more than one straight and level flight segment in the data as aircraft routinely climb or descend to different flight levels and make turns while in cruise. The ADS-B derived aircraft geometric heights which are quantized to 25 ft are smoothed to reduce any random noise and remove some of the effect of the quantization. The smoothing method used is a nonparametric regression based on the maximum likelihood estimation of a signal-in-noise model and is described in Ref. 14.

Ref. 14 also describes the processing of the meteorological data for use in the ASE software. The processing of the meteorological data involves the generation of a time series of pressure surface geometric heights corresponding to the aircraft flight-level for the times and locations coincident to the ADS-B data. The meteorological data is provided by the US NOAA. The processing of these data consists of converting the NOAA provided meteorological grid data of geopotential heights at six millibar levels to flight-level heights, and then converting from geopotential height above mean-sea-level to geometric height above the reference ellipsoid (WGS-84). The algorithms used to accomplish these tasks are described in Ref. 14.

The FAA-developed software provides an estimate of AAD, ASE, and TVE for each straight and level flight segment.

A. Treatment of the Level Flight Segments

Using the knowledge gained from work on the ASE estimation process using the portable EGMU systems and the ground-based AGHME systems, the FAA has applied some constraints to the resulting flight segment data to ensure quality results are achieved. One constraint imposed is a four minute minimum segment length placed on each straight and level segment observed in the data. The purpose of this time constraint is to ensure that the estimated ASE from the straight and level segment represents the aircraft’s performance for operation in an enroute cruise portion of flight and not in the middle of a turn or climbing/descending. Straight and level segments of short duration (less than four minutes) do not yield quality ASE results. This means that any straight and level flight segment with duration less than four minutes was not used to estimate aircraft ASE.

Another constraint imposed on the straight and level flight segments is the operation must have occurred within the RVSM flight level bands of FL 290 to FL 410. ASE experts have indicated that an individual aircraft’s ASE can vary by flight level. Because the purpose of estimating aircraft ASE is to ensure the continued safe-use of the RVSM, the flight level in which the RVSM is applied is of most interest.

B. Treatment of the Resulting Aircraft ASE
An average ASE value is estimated from each straight and level flight segment meeting the criteria explained in the above section. The number of individual ASE estimates in each straight and level flight segment can be numerous given that the ADS-B reporting frequency is approximately once every second. Aircraft ASE is expected to be relatively constant during the straight and level flight segment. Therefore, any straight and level flight segments with a resulting ASE range greater than 100 ft are removed. This rule was developed through the FAA’s experience with ASE processing with the EGMU and AGHME systems. Large ranges in ASE within a straight and level segment are not expected. Occurrences of such can indicate that the meteorological data was not accurate or that the ending or beginning portions of a climb/descend were included in the straight and level segment.

The straight and level flight segments for operations conducted within the RVSM flight levels bands, with a time duration greater than four minutes, and with a range of ASE within the segment not greater than 100 ft are referred to as valid straight and level flight segments in this paper.

VII. Analysis and Results

Aircraft ASE estimates were produced for each valid straight and level flight segment in the Australian data. One initial observation was that the length of the flight segment was much longer than a typical flight segment monitored by the AGHME or EGMU. Initially, the ASE estimates were examined by ADS-B ground station. Figure 5 contains box plots of the average ASE by ADS-B ground station. An Analysis of Variance (ANOVA) test was also performed on these data. ANOVA test can be used to test for differences among two or more independent samples. In this study, the independent samples are the ASE estimates produced from the valid straight and level flight segments observed at each ADS-B ground station. The null hypothesis of the ANOVA test is the ASE means observed at all of the ADS-B ground stations are equal. The ANOVA test result indicated there are significant differences in the ASE estimates by ADS-B ground station and that the null hypothesis should be rejected. There are many factors to be considered to determine the exact cause or causes for these differences. Some of the factors to be considered include the height-keeping performance of the individual airframes and characteristics of the aircraft group. In addition, the estimate of aircraft ASE is very sensitive to the meteorological data. It is possible that the quality of the meteorological data may vary by location and time of day. This paper is not suggesting that the ADS-B ground stations cause the observed differences, rather that a bias may be introduced into the results due to the available meteorological information for the airspace covered by the ADS-B ground station. The ADS-B ground station is used as a surrogate for the latitude/longitude region represented by the coverage area of the ADS-B ground station.

To evaluate the effect of the possible factors such as aircraft type, time of day, latitude/longitude region, flight level and meteorological data, valid straight and level flight segments from aircraft which operate over many different ADS-B ground stations were chosen. There were eighteen unique airframes observed by all seven ADS-B ground stations during a single day at least once in the nine day sample. The ASE results from these eighteen flights were closely examined. Of particular interest were the ASE comparisons from the straight and level flight segments observed at different ADS-B ground stations. Figures 6 through 9 show the results for two of these airframes, labeled as AC1 and AC2. Figures 6 and 7 show the individual ASE estimates for each ADS-B report from AC1 and AC2, respectively by ADS-B ground station, date, and time of day. The graphs below Figures 6 and 7, Figures 8 and 9, provide a closer examination of the data for AC1 and AC2 contained in Figures 6 and 7, respectively. The horizontal axes in Figures 8 and 9 shows the average ASE plotted at the day and time taken from the midpoint of the straight and level segment. For example, in Figure 9 the horizontal axis range is from 5.0 to 6.0, this means the data shown begin at the start of August 5 and end at the start of August 6. The ASE values estimated between 5.8 and
6.0 on the horizontal axis represent roughly 4.8 hours observed on August 5 between 19:12 UTC and 23:59 UTC. The vertical dotted lines in the figures represent the six-hour time stamps of the meteorological data updates in the ASE software. The data show similar ASE results obtained for the same airframe from different ADS-B ground stations – or for different latitude/longitude regions. The data presented in Figures 8 and 9 show clusters of ASE estimates from straight and level segments occurring within the same time period for the same airframe. Figure 10 shows a closer view of the estimates of ASE calculated at the end of the day on August 5 for AC2. Figure 10 shows the estimated geometric height of the flight level computed using the meteorological data and the smoothed geometric heights of the aircraft provided in the ADS-B reports. The geometric height of the flight level is shown using the color of the ADS-B ground station; the smoothed geometric height of the aircraft is plotted with red ‘x’s. The TVE is calculated as the difference between the aircraft geometric height and the flight level geometric height. Since the AAD for each flight segment shown in Figure 10 was zero, the estimate of ASE for the straight and level flight segment is equal to the TVE.
Figure 10 shows the estimated geometric height of the flight level estimated from the meteorological data is slightly higher than the geometric height of the flight level flown by the aircraft in two of the three segment groupings shown. One of the flight segments shown in Figure 10 shows the geometric height of the flight level obtained from the meteorological data to be slightly lower than the smoothed geometric height of the aircraft from the ADS-B reports.  These results are typical and have been observed for many flight segments in the data.

The average ASE by hour of the day was computed from all the data in the nine day sample.  Because the straight and level flight segments can be rather long, these estimates were made using the individual ASE point estimates from each ADS-B report instead of the mean ASE from each segment.  These data are shown by day and hour in Figure 11.  The average numbers of ASE point estimates by hour of the day are shown in Figure 12.  Figure 12 provides an estimate of the level of traffic volume observed by the seven ADS-B ground stations throughout the day.  Although there are many additional factors for consideration, such as aircraft type, flight level, and latitude/longitude region; there is evidence of an offset from zero in Figure 11.  In addition, Figure 11 shows a consistent pattern in the data shown by time of day.  It is expected that the data shown in Figure 11 would exhibit a random pattern about zero.

![Figure 11. ASE by Time of Day for the Nine-Day Sample](image)

![Figure 12. Average Number of ASE Point Estimates by Time of Day for the Nine-Day Sample](image)
VIII. Conclusion

This paper progresses the evaluation of using ADS-B data to estimate the ASE for aircraft in the United States contained in Ref. 4. The results of the test flights conducted at the FAA Technical Center with the WAAS corrections disable demonstrated that the geometric height information contained in the ADS-B data is sufficiently accurate to estimate aircraft ASE under uncontrolled conditions. In addition, one conclusion from Ref. 4 related to an apparent bias observed in the 1090 ES data was shown to be false.

This paper also examines the ASE estimates resulting from data collected as a result of a cooperative effort between the FAA and Airservices Australia. The ASE estimate process was applied to these data collected from a real airspace operational environment. It was determined that additional processing and quality control procedures were needed in order to utilize the geometric heights recorded in the ADS-B data. The FAA applied some of the quality control procedures developed for the AGHME ground-based monitoring system. The minimum duration for the straight and level segment was set to four minutes, and the maximum ASE range for each straight and level segment was 100 ft. Straight and level flight segments not meeting these criteria were removed. The resulting data were numerous. Due to the range of the ADS-B ground stations, several of the straight and level flight segments had very long durations. It was expected that the ASE results from all observations would have an average value close to zero; however this was not observed in these data. There appears to be a bias in the ASE results obtained from the ADS-B reports in Australia. Further investigation into straight and level segments from aircraft which operate over all the ADS-B ground stations used in the data show some differences in the time of day. This result was confirmed using all of the ASE data obtained from ADS-B reports for the nine-day sample.

IX. Future Work

Further investigation is needed into the meteorological data for use in estimating aircraft ASE from ADS-B reports in Australia. Alternate sources of meteorological data and/or more frequent updates will be explored as the work progresses. Once the questions regarding the meteorological data are resolved further validation of this application of the ADS-B will be needed. Validation and verification will be accomplished with comparisons of ASE results for specific airframes and aircraft groups between the ADS-B and other monitoring sources such as the EGMU, AGHME and HMU systems. Throughout the validation process additional quality control techniques will be developed and applied to the data. The knowledge gained from undertaking this study will provide the FAA with ability to apply these same processes to ADS-B reports collected from the US NAS allowing for another RVSM monitoring option for aircraft operators.

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