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Investigation into the use of 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. In preparation for the implementation of the RVSM, the Federal Aviation Administration (FAA) developed a process to monitor the height-keeping performance of aircraft. This process uses a portable device, called the Enhanced Global Positioning System (GPS)-based monitoring unit (EGMU) which is placed on board an aircraft. The International Civil Aviation Organization (ICAO) is developing long-term minimum monitoring requirements to be used by the regions where the RVSM is implemented. This paper considers the role of a new technology, Automatic Dependent Surveillance–Broadcast (ADS-B), to monitor the height-keeping performance of aircraft. The FAA Technical Center conducted flight tests to compare aircraft geometric height obtained from three sources; ADS-B, EGMU, and an onboard independent GPS reference receiver. This paper contains the comparisons of the aircraft geometric height from the three sources. The results of this study will be used to determine whether ADS-B geometric height data is sufficient for use in estimating aircraft ASE.

I. Introduction

THE Federal Aviation Administration (FAA) introduced the Reduced Vertical Separation Minimum (RVSM) between flight levels (FL) 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 2000 ft to 1000 ft. This reduction followed successful implementations of RVSM in numerous 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 with 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. Contained in this document are requirements for the monitoring of aircraft altimetry system error (ASE). ASE is defined in the document 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. ASE is not detectible 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, ICAO has developed standards that aircraft must meet in order to operate in RVSM airspace. An aircraft must maintain an airworthiness approval, which states that each designated aircraft

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group must possess a mean ASE value less than 80 ft in magnitude, and the absolute value of the mean plus three standard deviations must be less than 245 ft.

ICAO regional bodies have developed minimum monitoring requirements, which provide the required proportion of operator airframes needed to obtain RVSM approval. Ten years after the first implementation of the RVSM (in North Atlantic oceanic airspace), the ICAO is now developing long-term monitoring requirements. This paper considers the role of a new technology, Automatic Dependent Surveillance–Broadcast (ADS-B), for use in monitoring the height-keeping performance of aircraft.

The FAA Technical Center conducted flight tests to determine whether the geometric height data contained in ADS-B messages is sufficient for computing aircraft ASE. The FAA Technical Center use the data collected during these flight tests to compare aircraft geometric height obtained from three sources; ADS-B, Enhanced GPS-based Monitoring Unit (EGMU), and an onboard highly accurate independent GPS reference receiver. This paper contains the comparisons of the aircraft geometric height from the three sources. The results of this study will be used to determine whether ADS-B geometric height data is sufficient for use in estimating aircraft ASE.

II. Background

Prior to any changes in separation standards, ICAO requires an evaluation of the collision risk for the target airspace. The vertical collision risk estimate is divided into two components; operational and technical risk. Operational risk is the risk associated with human errors, including the failure of a pilot to correctly follow a clearance or the controller issuing an incorrect clearance. Technical risk is the risk associated with aircraft height-keeping systems. Technical errors consist of ASE and Flight Technical Errors (FTE). The ASE is a measure of the aircraft system's ability to correctly evaluate and convert ambient static pressure to the height corresponding to the ICAO Standard Atmosphere (Ref 2). 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.

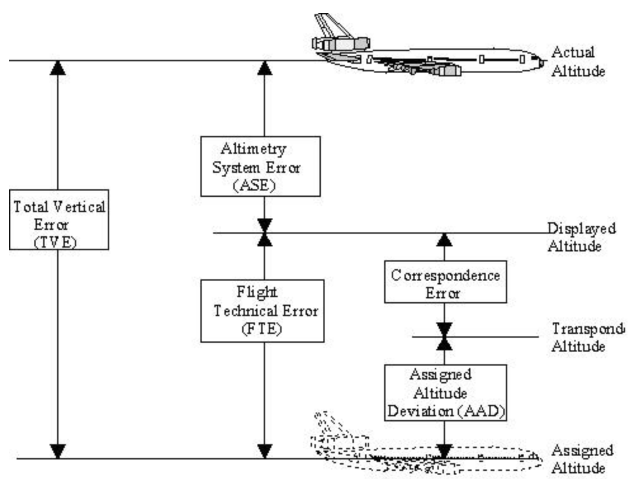

Figure 1. Components of Total Vertical Error (TVE)

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 by the static probe is the actual ambient pressure. As a result it is necessary to assure that the aircraft systems are designed and maintained to control the magnitude of ASEs (Ref 3).

In preparation for the implementation of the RVSM, the FAA developed a process to determine Total Vertical Error (TVE), ASE and AAD for individual aircraft. One method of estimation uses a portable device, the EGMU, which is placed on board an aircraft; it collects GPS pseudo-ranges through the placement of antennae on the aft windows of the aircraft. These data are then post-processed and differentially corrected to improve their accuracy and aircraft position is estimated, which results in aircraft geometric height data referenced to the World Geodetic System (WGS)-84 ellipsoid. The corrected geometric height information is compared to the geometric height of the flight level flown by the aircraft, with the latter obtained using global meteorological model data. The EGMU also collects Mode C or Mode S returns for the flight with its Altitude Recorder Device (ARD) component, producing data used to estimate AAD. All three of these data sources are then combined in a process which estimates TVE and then resolves ASE.

Aircraft ASE is computed by EUROCONTROL and the North Atlantic (NAT) Central Monitoring Agency (CMA) using a ground-based system, the Height Monitoring Unit (HMU). There are four HMUs - three in Europe and one in the United Kingdom. Ref 3 describes the test flights and study which supported the use of the HMU and GMU for monitoring aircraft height-keeping performance. The study contained in Ref 3 was completed prior to the initial implementation of the RVSM in the North Atlantic.

The FAA also uses a ground-based system to compute aircraft ASE, the Aircraft Geometric Height Measurement Element (AGHME). Unlike the HMU which produces estimates of TVE, ASE and AAD directly, the AGHME estimates aircraft geometric height through a multi-lateration technique. The FAA's post-processing which determines the estimates of TVE and ASE using AGHME-derived aircraft geometric height is the same method as that used for the EGMU. Currently, there are five AGHME systems operational in North America, three in the United States and two in Canada. A sixth AGHME is under construction in the western United States.

ADS-B allows equipped aircraft to automatically broadcast their position, velocity, and other information between each other and to the ground for air traffic control purposes[4]. ADS-B equipped aircraft use an on-board 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 centers. ADS-B data includes estimates 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 National Airspace System (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[5].

The FAA Technical Center's ADS-B Surveillance Team is studying the potential uses of ADS-B technology in the U.S. airspace. The FAA is currently in the process on increasing the ADS-B ground network infrastructure in the U.S. Numerous other countries are also initiating programs to include ADS-B as components of their Air Traffic Service Systems. Geometric height, which is included in the ADS-B messages, is an important component in the calculation of ASE. As long as the RVSM is in place, the aircraft that operate in such airspace will be required to undergo periodic monitoring for height-keeping performance. The purpose of this study is to determine whether the geometric height information contained in the ADS-B data is sufficiently accurate to estimate aircraft ASE. If so, the expansion of ADS-B technologies would greatly aid the task of monitoring aircraft height-keeping performance.

III. Review of Related Studies

Prior to the first implementation of the RVSM, the FAA and EUROCONTROL participated in a study which compared the ASE estimation processes of the two existing monitoring systems of that time, the HMU and GMU. Ref 3 describes the test flights and comparison methodology used for this study. The main objective of the study was to compare the HMU and the GMU as monitoring tools for aircraft height-keeping performance. The study focused on two areas. It first described the differences between HMU and GMU estimated TVE and ASE values from the test flights performed. The results showed that the measured geometric height obtained from the HMU was an average of 10 ft below the measured geometric height obtained from the GMU. Also, the measured flight-level height obtained from the HMU was an average of 50 ft below the measured flight level height obtained from the GMU. The resulting average difference in TVE between the HMU and GMU was 40 ft. Ref 3 also describes differences in the geometric height estimates of flight-levels as provided by the source of meteorological data and as subsequently adjusted by the two monitoring systems. Overall, the two monitoring systems compared well, the main differences were attributed to the geometric height estimates of flight level produced from the individual meteorological models and processes of each system. Therefore, the primary focus of this study is in the comparison of geometric heights estimated from the systems involved. ASE is estimated from each system as well and those derived data are presented. It should be noted that the technique for determining the flight level geometric height is consistent between the systems.

There is a current study, being conducted by Airservices Australia, which considers the possibility of monitoring height-keeping performance utilizing aircraft geometric height data obtained from ADS-B data. The status of this study is described in Ref. 6. However, the method for estimating aircraft ASE is different from that used by the FAA. The aircraft ASE estimation process presented in Ref. 6 utilizes ADS-B data from pairs of aircraft. Using this method, values of a height difference parameter between one aircraft and many other aircraft are averaged to predict the ASE of the first aircraft. Here, the ASE contributions from all the other aircraft are expected to have zero mean. Any calculated non-zero ASE is thus attributed to the first aircraft[6].

IV. Data Sources and Descriptions

A. Test Flights

The FAA Technical Center has a fleet of research aircraft that are used for conducting tests and evaluations of avionics systems. One of these aircraft, N47 – a Bombardier BD-700-1A11 aircraft, was used for this study. This aircraft has ADS-B capabilities, but prior to our study, was not used for ADS-B test purposes at altitudes above FL290. The RVSM flight levels in U.S. domestic airspace, and the flight level bands of interest for height-keeping performance monitoring, are FL290 through FL410. Therefore, data collection equipment needed to be adjusted to allow for the receipt of the ADS-B messages to a ground receiver prior to conducting the test flights. In addition a 1090 Extended Squitter (ES) suite of test avionics had to be constructed for the aircraft. The aircraft is equipped with two GPS antenna on top of the aircraft. Each antenna provides a source for independent GPS data, the study refers to these data as truth data. The antenna located on the top right side of the fuselage is the source for one set of truth data along with the Universal Access Transceiver (UAT) Data Link. The antenna located on the top left side of the fuselage is the source for a second set of truth data and the 1090 ES. Both the UAT and the 1090 ES are described in more detail in the next section.

The three test flights conducted for this study consisted of a series of four level flight segments and occurred during the time period of June 26, 2008 to July 2, 2008. The flights departed from the Atlantic City International Airport (ACY) in Atlantic City, New Jersey. The first segment began in Atlantic City and ended over Gibbsboro, NJ. The second and third segments of the test flight traversed between Barnegate, NJ and Millville, NJ. The final segment began over Gibbsboro, NJ and returned to Atlantic City, NJ. An example of the flight path is shown in Figure 2.

Table 1. Summary of Test Flights

Date of Test Flight and Segment Number	Duration (minutes)	FL
June 26 – Segment 1	9	280
June 26 – Segment 2	12	280
June 26 – Segment 3	10	280
June 26 – Segment 4	7	280
June 27 – Segment 1	10	280
June 27 – Segment 2	11	280
June 27 – Segment 3	10	410
June 27 – Segment 4	8	410
July 2 – Segment 1	8	280
July 2 – Segment 2	12	280
July 2 – Segment 3	3	410
July 2 – Segment 4	7	410

The first flight took place on June 26, 2008. All of the segments of this flight were flown at FL280. The second test flight occurred on June 27, 2008. The first two segments of this flight were flown at FL280 and the second two segments were flown at FL410. All three data types were collected for the first two flights. The final test flight took place on July 2, 2008 at FL280 for the first two segments and FL410 for the last two segments. Due to a problem with the 1090 ES receiver, it was not possible to collect 1090 ES data during this test flight; UAT, EGMU and truth data were collected. Table 1 summarizes the test flights, including the length of each segment and the altitude.

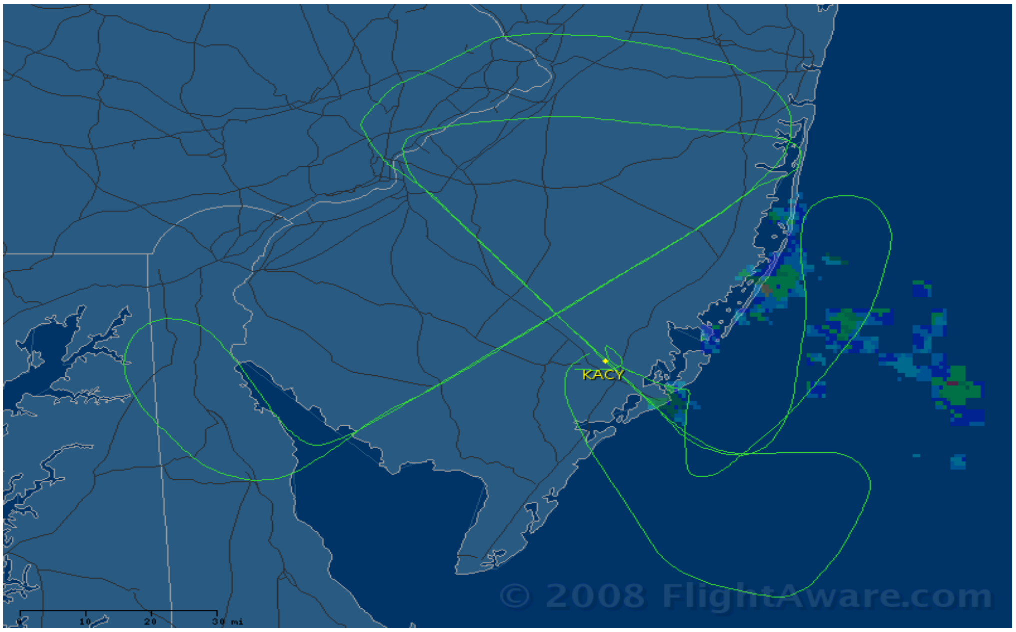

Figure 2. Example of Flight Path during Test Flights

B. ADS-B Data

The ADS-B data from the test flights were collected using two different systems. Both systems collect data from closely mounted GPS antenna mounted on the roof of the aircraft. The data is then sent to two separate Wide Area Augmentation System (WAAS) enabled GPS receivers, the UAT system uses a Garmin GPS receiver and the 1090 ES system uses a Rockwell Collins GNLU-930 Multi-Mode Receiver. The UAT system and Garmin receiver are typical of general aviation type aircraft while the 1090 ES system and Rockwell Collins receiver are typical of commercial type aircraft.

The treatment of the GPS-derived geometric height is different for each of the 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 1090 ES data required some preprocessing before comparisons could be made with the truth data. These data consist of several different message types; each message contains a message type number. The message types of interest are 10, 11 and 19. Message Type 19 contains the time and the difference between the geometric altitude and the pressure altitude; Message Types 10 and 11 contain the time, pressure altitude and the latitude and longitude. To compare these data with the truth data, the two data sets are time matched and the geometric altitudes are computed from the given pressure altitude and the difference between the geometric altitude and the pressure altitude. The latitude/longitude position information is used to ensure that the time matching has been done correctly. Because the time matching is critical to the comparison process, it would be ideal for the data to contain the geometric altitude and latitude/longitude position for each reported time. The time matching process begins by computing the geometric altitude by adding the pressure altitude contained in Message Type 10 or 11 to the difference between the geometric altitude and the pressure altitude contained in Message Type 19. The latitude/longitude position contained in the type 10 or 11 message is appended to the time and geometric altitude computed from the two messages to compose one data record.

Each record in the UAT data already contains the time, position and geometric altitude. Therefore, these data were not preprocessed prior to the comparisons with the truth data.

The time field in both the 1090 ES messages and the 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.

C. Truth Data

The geometric heights in the truth data are obtained from an independent Ashtech Inc. GPS receiver. These data were also available from the test flights. 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 time field in the truth data is in GPS time (currently a 14-second offset from UTC), the geometric altitude is measured in meters with precision to the ten thousandth of a meter.

D. EGMU Data

Additionally, an EGMU was brought onboard the aircraft; data from this system were processed in the same manner established for monitoring ASE in the initial implementation of the RVSM. The aircraft geometric height data obtained from the EGMU is differentially corrected through post-processing. Meteorological data, needed to determine the geometric height of the assigned flight level, are obtained from the National Weather Service. The time in the EGMU data is collected using GPS time and the geometric altitude is measured in feet with precision to the one hundredth of a foot.

V. Methodology

In order to determine if the geometric heights contained in the ADS-B data would be suitable for the estimation of ASE a comparison is made between the geometric heights in both sources of the ADS-B data and the EGMU data with the truth data. This comparison is sufficient in determining if the ADS-B data can be used as a data source to determine ASE estimates 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. Currently, many aircraft ASE estimates in the United States are computed using data collected by the EGMU. It is important to compare the results obtained from the EGMU with the results from the sources of ADS-B data in order to determine if the geometric heights contained in the ADS-B data are comparable to those obtained from a source that has been proven reliable in the estimation of ASE.

A. Treatment of the Aircraft Geometric Height Estimates

To compare the aircraft geometric heights from both sources of ADS-B data and EGMU data with the aircraft geometric heights in the truth data, the data must be synchronized in time. Both sources of ADS-B messages contain two time values; one time value indicates the time the message is composed onboard the aircraft and the other time value is the time stamp indicating the time the message is received on the ground. When comparing the ADS-B data to the truth data, the time of interest is the time at which the message is composed since that corresponds to the position included in the message. The time included in the ADS-B message is in UTC time. Additional fields of interest in the ADS-B data include the latitude, longitude, and geometric heights, which are provided in units of feet.

The truth data contains similar information; however, the time included in these data is GPS time. Currently, GPS time is ahead of UTC by 14 seconds. Both the ADS-B timestamp and truth system are derived from GPS and considered to be highly accurate. Other fields of interest in the truth data include the latitude, longitude and geometric heights which are provided in meters. Corrections are made to the time in the ADS-B messages and the geometric heights in the truth data so that the units in both data sources match.

B. Comparisons of Aircraft Geometric Height Data from ADS-B, EGMU and Truth Data

The ADS-B data provides a position estimate approximately once every second. The truth data provides more frequent estimates, approximately 4 to 5 times a second. Comparisons of the ADS-B data with the truth data were completed using the reports containing the time which most closely matched the time in the ADS-B report. The geometric height in the ADS-B data was then subtracted from the geometric height contained in the truth data.

The differences were computed for all of the data collected during the test flights, however, the data of most interest are those collected during level flight segments. Each test flight consists of four level flight segments. Table 3 shows the average difference in geometric heights between the 1090 ES data and the truth data for each of the level flight segments. It also contains the standard deviations of the differences of the geometric heights. Data was only available from the 1090 ES during the first two test flights. Table 4 shows a comparison between the UAT data and the truth data. Table 5 shows a comparison between the EGMU data and the truth data. For each of these comparisons level flight segments during all three test flights were used.

Table 3. Comparison of Geometric Heights from ADS-B 1090 ES and Truth Data

Date of Test Flight and Segment Number	Number of Data Points	Average Difference in Geometric Height (feet)	Standard Deviation of Differences in Geometric Height
June 26 – Segment 1	195	-18.1687	4.5510
June 26 – Segment 2	235	-21.1349	8.8493
June 26 – Segment 3	182	-17.8488	10.0570
June 26 – Segment 4	99	-20.9199	9.8452
June 27 – Segment 1	230	-28.3611	11.4985
June 27 – Segment 2	226	-25.5960	12.1417
June 27 – Segment 3	125	-22.7844	6.8789
June 27 – Segment 4	18	-24.5452	12.3172

Table 4. Comparison of Geometric Heights from ADS-B UAT Data and Truth Data

Date of Test Flight and Segment Number	Number of Data Points	Average Difference in Geometric Height (feet)	Standard Deviation of Differences in Geometric Height
June 26 – Segment 1	262	4.8788	6.7913
June 26 – Segment 2	349	3.8801	7.6733
June 26 – Segment 3	300	1.4220	7.5286
June 26 – Segment 4	213	9.5898	8.2456
June 27 – Segment 1	275	5.0884	7.0444
June 27 – Segment 2	330	3.8616	7.7387
June 27 – Segment 3	293	2.6456	6.6232
June 27 – Segment 4	220	3.0625	7.0834
July 2 – Segment 1	49	0.3317	6.5839
July 2 – Segment 2	78	5.1573	7.5477
July 2 – Segment 3	17	6.1473	7.7315
July 2 – Segment 4	46	7.4033	8.1233

Table 5. Comparison of Geometric Heights from EGMU Data and Truth Data

Date of Test Flight and Segment Number	Number of Data Points	Average Difference in Geometric Height (feet)	Standard Deviation of Differences in Geometric Height
June 26 – Segment 1	104	7.8501	3.8747
June 26 – Segment 2	89	6.9538	1.8676
June 26 – Segment 3	136	5.5734	1.6290
June 26 – Segment 4	153	14.8335	5.3290
June 27 – Segment 1	197	10.5263	2.9753
June 27 – Segment 2	228	7.6512	2.4742
June 27 – Segment 3	159	0.5592	5.3641
June 27 – Segment 4	167	-0.9596	4.6323
July 2 – Segment 1	490	7.2574	1.0506
July 2 – Segment 2	737	4.6388	1.5596
July 2 – Segment 3	197	3.3440	1.2046
July 2 – Segment 4	437	4.3239	2.8609

A correction is applied to the EGMU data to account for the vertical displacement between the locations of the antenna which measure the geometric height of the aircraft. The EGMU uses an antenna that is mounted on the window of the aircraft while the geometric altitude in the truth data is determined using an antenna mounted on the top of the aircraft. This will cause a difference between each system’s estimate of the geometric height of the aircraft. The distance between the center of the window and the top of the aircraft is 41.5 inches. This amount was subtracted from the difference between the geometric height in the truth data and the geometric height in the EGMU data.

The following two figures illustrate some of the initial analyses performed on the three sets of data. The box plots in Figure 3 illustrate the ranges of the data sets. The horizontal bars above and below the boxes represent the highest and lowest value of the data sets respectively. The bottom of the box is the first quartile, the white line in the center of the box is the median of the data or the second quartile and the top of the box is the third quartile. 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. Since the range of the data from the 1090 ES does not overlap either of the other two data sets it may have different characteristics than the UAT and EGMU data. Figure 4 shows a comparison of the geometric heights from the 1090 ES, the UAT and the truth data. The time, in seconds, of the level flight segment is along the x-axis and the geometric altitude is on the y-axis. The UAT data and the 1090 ES data are plotted along with the truth data in order to show the differences in each of the data sets. The data are from the first level flight segment of the test flight on June 26, 2008.

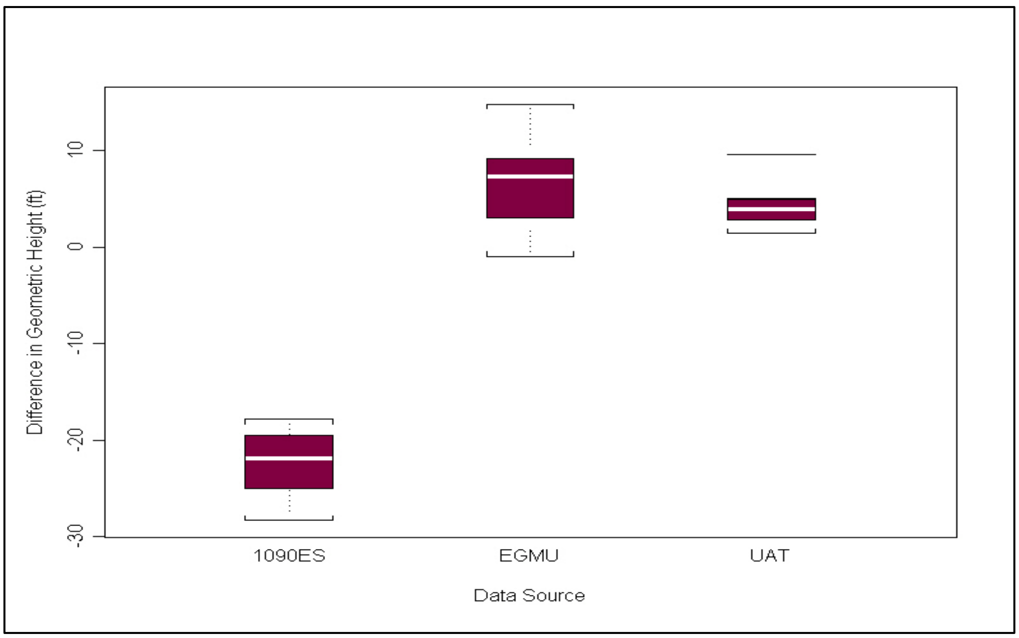

Figure 3. Box Plots of the ADS-B data and the EGMU data

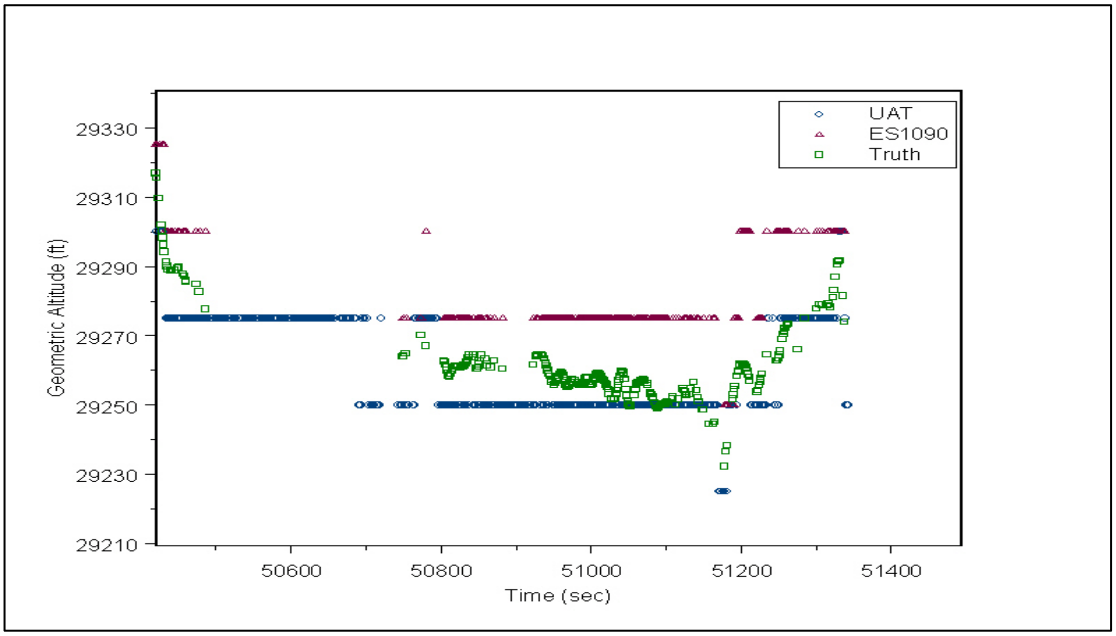

Figure 4. ADS-B and Truth data for June 26, 2008 Segment 1

Both the 1090 ES and UAT are quantized to 25 ft, while the truth data is accurate to one thousandth of a foot. It can be seen from Figures 3 and 4 along with the summary of the differences in geometric altitudes in Tables 3 and 4 that the geometric altitudes in the 1090 ES data and the UAT data differ by an average of approximately 26 ft. Prior to conducting the test flights, it was expected that the aircraft geometric height from the two ADS-B sources, UAT and 1090 ES, would produce similar results when compared to the truth data. Both sources of ADS-B data obtain the aircraft geometric height information from identical antenna, in the same location on the aircraft and are both WAAS corrected. The observed differences in the aircraft geometric height from the UAT and 1090 ES triggered an investigation into each system's treatment of the aircraft geometric height before the information is sent down to the ADS-B ground receiver.

As was mentioned earlier both the 1090 ES and the UAT data are quantized to 25 ft, however the investigation into each system's internal treatment of the aircraft geometric height revealed that the two systems arrive at the estimate of geometric height differently. The geometric heights collected by the UAT on board the aircraft are rounded to a 25 ft increment prior to being sent to the ground receiver[4]. The expected value and the variance of the difference of the true aircraft geometric heights from the UAT data are defined in Appendix A.

The expected value of the geometric height obtained from the UAT source has three potential outcomes, which is determined by the rounding method. All three potential outcomes involve the addition of a rounding error to the geometric height data. In the first potential outcome, the geometric height data are rounded up or down to the nearest 25 ft increment. In this case, the rounding error is a uniform random variable with a range of -12.5 to 12.5 ft and a mean equal to zero. In the second potential outcome, the geometric height data are rounded up to the nearest 25 ft increment. In this case, the rounding error is a uniform random variable with a range of 0 to 25 ft and a mean equal to 12.5 ft. Finally, for the third potential outcome, the geometric height data are rounded down to the nearest 25 ft increment. In this case, the rounding error is a uniform random variable with a range of -25 to 0 ft and a mean equal to -12.5 ft. The UAT data collected for this study have an average difference from the truth data of 4.303 ft. This result supports the assumption that the rounding process for the UAT data follows the first potential outcome and are rounded up or down to the nearest 25 ft. increment.

The 1090 ES collects the pressure altitude, which is rounded to a 25 ft increment. The 1090 ES also provides the difference between the aircraft geometric altitude and the pressure altitude, this difference is also rounded to a 25 ft increment[7]. The pressure altitude and the difference between the aircraft geometric height and the pressure altitude are sent to the ADS-B ground receiver. During post processing, the difference between the aircraft geometric altitude and the pressure altitude are added to the pressure altitude to determine the aircraft geometric altitude. This addition produces an estimate of aircraft geometric altitude from the sum of two values which were previously rounded to a 25 ft increment. The expected value and variance of the true aircraft geometric height in relation to the 1090 ES data are presented in Appendix A.

Similar to the UAT geometric height data, there are also three potential outcomes for the expected value of the geometric height contained in the 1090 ES data as long as both sources receive similar treatment. Since the geometric height is determine by adding two values that are rounded, the rounding error added to the geometric height in the 1090 ES data is a sum of two errors created during the rounding of both values. In the first potential outcome, the geometric height data are rounded up or down to the nearest 25 ft increment. In this case, each rounding error is a uniform random variable with a range of -12.5 to 12.5 ft and the mean of each error equal to zero. In the second potential outcome, the geometric height data are rounded up to the nearest 25 ft increment. In this case, the rounding errors are uniform random variables with ranges of 0 to 25 ft and the mean of each error is 12.5 ft. This leads to an overall error included in the expected value of the 1090 ES geometric height data of 25 ft. In the third potential outcome, the geometric height data are rounded down to the nearest 25 ft increment. In this case, the rounding errors are uniform random variables with ranges of -25 ft to 0 and the mean of each error is -12.5 ft. This leads to an overall error included in the expected value of the 1090 ES geometric height data of -25 ft. The data collected for this study have an average difference from the truth data of -22.419 ft, this means the 1090 ES geometric height data is on average 22.419 ft higher than the truth data. These data support the assumption that the rounding process for each element of the 1090 ES data follows the second potential outcome and are rounded up to the nearest 25 ft increment.

Figure 4 showed an example of the effect of the rounding errors. The aircraft geometric height obtained from the 1090 ES, when plotted with the aircraft geometric height obtained from the truth and UAT data, is observed to have higher values. The 1090 ES remains 25 ft higher than the UAT data for most of the level flight segment.

VI. Analysis and Results

A. Analysis of Variance Test

Analysis of Variance (ANOVA) test are used to test for differences among two or more independent samples. In this study the independent samples are each of the measurement systems. In this case comparisons will be made between the differences between each of the sources and the truth data. Each level flight segment of the test flights represents one replication. Only the tests flights from June 26 and 27 will be used for this analysis because all four data sources were not available during the July 2 test flight. The null hypothesis for this study tests whether there is a difference between the mean differences in geometric heights when comparing each data source to the truth data. The null hypothesis is tested at a 95% confidence level. Table 6 contains the results of the ANOVA analysis.

Table 6. ANOVA Table

Groups	Count	Sum (ft)	Average (ft)	Variance (ft)		
EGMU	8	52.987	6.623	25.812		
1090 ES	8	-179.359	-22.419	13.272		
UAT	8	34.428	4.303	5.979		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	4168.122	2	2084.061	138.738	7.88E-13	3.466
Within Groups	315.451	21	15.021			
Total	4483.573	23				

The null hypothesis is rejected, the mean difference between the three independent sources of aircraft geometric height and the aircraft geometric height obtained from the truth data are significantly different. The P-value in the ANOVA Table provides an indication as to the validity of the null hypothesis; the very small P-value indicates that the null hypothesis should be rejected. The ANOVA table is used to analyze the differences between the mean values of all three samples. Since there is a difference between the way the 1090 ES data and the UAT data determine the geometric heights it is useful to compare each of these data sets to the EGMU data separately. A T-test can be used to compare the means of two samples. The results of the T-test show that the null hypothesis that the mean difference between the geometric heights obtained from 1090 ES data and the truth data and the mean difference between the EGMU data and the truth data can be rejected. However the null hypothesis that the mean difference between the UAT and truth data and the EGMU and truth data are different can not be rejected. Both of these results are tested against a t-Critical value with a 95% confidence level. These results are summarized in Table 7.

Table 7. T-test Results

Null Hypothesis	T statistic	P(T<=t)	t Critical	Results
$\mu_{EGMU} = \mu_{1090ES}$	13.388	0.000	2.365	reject null hypothesis
$\mu_{EGMU} = \mu_{UAT}$	1.890	0.101	2.365	null hypothesis can not be rejected

The expected value of the geometric height included in the 1090 ES data may contain a bias of 25 ft, which has caused the data to be statistically different from both the UAT and the EGMU data. This apparent 25 ft bias was removed from the 1090 ES data and the ANOVA analysis was performed a second time. The results of this analysis are shown in Table 8. At a 95% confidence level the null hypothesis can not be rejected. The results of this test indicate that with the apparent 25 ft bias removed from the 1090 ES data, the means of the three samples are not significantly different.

Table 8. ANOVA Table with 25 ft Bias Removed

Groups	Count	Sum (ft)	Average (ft)	Variance (ft)		
EGMU	8	52.987	6.623	25.812		
1090 ES	8	20.641	2.580	13.272		
UAT	8	34.428	4.303	5.979		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	65.866	2	32.933	2.192	0.137	3.467
Within Groups	315.457	21	15.022			
Total	381.321	23				

B. ASE Results

Table 9 shows the ASE estimates for the test flights computed using data collected from both the EGMU system and the ADS-B systems on June 27, 2008 and July 2, 2008. It was not possible to compute the ASE values for the test flight on June 26 because the ASE software, developed at the FAA Technical Center, utilizes data obtained from flights operating with RVSM flight levels, FL290 through FL410. The flight on June 26 was flown at FL280.

The aircraft ASE estimated using the data collected from the UAT system compares very closely to the aircraft ASE estimated from the EGMU data in all of the level flight segments. When the apparent 25 ft bias was removed from the 1090 ES data the estimates of aircraft ASE computed were much closer to the ASE values estimated with the EGMU and UAT data. The aircraft ASE estimated with the aircraft geometric height obtained from the 1090 ES system was computed for June 27 only due to a problem with the ground receiver during the July 2 test flight.

Table 9. ASE Estimates for Data Collected During the Flight Test on June 27 and July 2

Segment and Flight Level	Data Source	ASE	Number of Observations
June 27 FL 410	EGMU	73	188
	1090 ES	95	176
	1090 ES – 25 ft bias	70	176
	UAT	73	310
June 27 FL 410	EGMU	111	137
	1090 ES	149	65
	1090 ES – 25 ft bias	124	65
	UAT	118	173
June 27 FL 410	EGMU	78	155
	1090 ES	Insufficient Data	5
	UAT	76	155
July 2 FL 410	EGMU	57	647
	UAT	58	58
July 2 FL 410	EGMU	55	468
	UAT	50	46

VII. Conclusion

This paper provides an evaluation of the possibility of using ADS-B data to estimate the ASE for aircraft in the United States. Aircraft geometric height is a major component to the estimation of ASE therefore the analysis focused mainly on the comparison of the aircraft geometric heights obtained from two sources of ADS-B data. The truth data collected during the test flights were used to test the accuracy of the aircraft geometric height estimates in each of the ADS-B data sources; UAT and 1090 ES. The EGMU data collected allowed for the comparison between the ADS-B data sources and a data source that has been proven accurate in estimating ASE.

During the examination of the data from the ADS-B data sources, differences in the way the UAT and the 1090 ES collect and treat the data were discovered. These differences directly contribute to differences in the estimates of aircraft geometric heights from the two systems. In the U.S., the FAA intends to use both ADS-B systems; the UAT system will be used by mainly general aviation aircraft while the 1090 ES will be used by commercial operations.

Both the UAT and 1090 ES data used in this study were WAAS corrected. The FAA ADS-B surveillance team indicated that all UAT systems use WAAS corrected data. Therefore, it is expected that the aircraft geometric heights obtained from other UAT equipped aircraft would have similar means and standard deviations if compared to truth data as shown in the results from this study. WAAS corrections may not always be applied in a 1090 ES system, which may lead to differences in the geometric heights collected by the system.

The mean aircraft geometric height estimates obtained from the UAT system was not significantly different from the mean aircraft geometric height estimates obtained from the EGMU. The EGMU is a proven and validated system for estimating aircraft ASE. Therefore, it is expected that ADS-B aircraft geometric height data obtained from a UAT system would produce similar ASE results as the EGMU. Because WAAS corrections are applied in all UAT systems, further testing for UAT aircraft geometric height data without WAAS corrections is not possible.

When adjusted for the apparent 25 ft bias, the mean aircraft geometric height estimates obtained from the 1090 ES was not significantly different from the EGMU estimates. However, the 1090 ES aircraft geometric height data were WAAS corrected. The FAA Technical Center is planning to conduct additional test flights with and without the WAAS corrections to determine whether the ADS aircraft geometric height obtained from all 1090 ES systems are suitable for estimating aircraft ASE. The additional analysis is critical because the operations conducted within RVSM flight levels, FL290 through FL410, require periodic monitoring for ASE performance. If aircraft geometric height data obtained from ADS-B were used for the RVSM operations, the data would be in the 1090 ES format. Additional data will also be collected on future test flights to determine the exact manner in which the data is rounded by both the UAT and 1090 ES systems.

APPENDIX A

Modeling of Expected Value and Variance for UAT Aircraft Geometric Height

UAT aircraft geometric height estimates are GPS height measurements rounded to 25 foot increments and are derived from the aircraft's L1 WAAS enabled GPS receiver. For both the expected value and variance of the geometric height, the model considers that rounding could occur in one of three manners, the first is rounding up to the nearest 25 foot increment, followed by rounding to the nearest 25 ft increment and finally rounding down to the nearest 25 foot increment.

Let h_u = rounded(GPS height) where h_u = UAT geometric height estimate
then h_u = rounded($h_t + e_n$) where h_t = true height of the aircraft
e_n = random error $N(0,\sigma)$

Therefore h_u can be rewritten as

$h_u = h_t + e_n + e_r$ where e_r = rounding error $U[a,b]$

with $E(h_u)$ and $Var(h_u)$ as

$$E(h_u) = E(h_t + e_n + e_r) \\ = E(h_t) + E(e_n) + E(e_r)$$

If the data is rounded up or down, then $U[a,b] = U[-12.5,12.5]$

$$E(h_u) = E(h_t) + E(e_n) + E(e_r) \\ = E(h_t) + 0 + 0 \\ = E(h_t)$$

If the data is rounded up, then $U[a,b] = U[0,25]$

$$E(h_u) = E(h_t) + E(e_n) + E(e_r) \\ = E(h_t) + 0 + 12.5 \\ = E(h_t) + 12.5$$

If the data is rounded down, then $U[a,b] = U[-25,0]$

$$E(h_u) = E(h_t) + E(e_n) + E(e_r) \\ = E(h_t) + 0 - 12.5 \\ = E(h_t) - 12.5$$

Since the rounding error e_r depends upon the value of ($h_t + e_n$)

$$Var(h_u) = Var(h_t + e_n + e_r) \\ = Var(h_t + e_n) + Var(e_r) + 2Cov((h_t + e_n), e_r) \\ = Var(h_t + e_n) + Var(e_r) + 2[E((h_t + e_n)e_r) - E(h_t + e_n)E(e_r)]$$

If $U[a,b] = U[-12.5,12.5]$, then
$$Var(h_u) = Var(GPS) + 625/12 + 2E((h_t + e_n)e_r) - 0$$

If $U[a,b] = U[0,25]$, then
$$Var(h_u) = Var(GPS) + 625/12 + 2E((h_t + e_n)e_r) - 2E(GPS)(12.5) \\ = Var(GPS) + 625/12 + 2E((h_t + e_n)e_r) - 25E(GPS)$$

If U[a,b] = U[-25,0], then

$$Var(h_u) = Var(GPS) + 625/12 + 2E((h_t + e_n)e_r) + 2E(GPS)(12.5)$$
$$= Var(GPS) + 625/12 + 2E((h_t + e_n)e_r) + 25E(GPS)$$

Modeling of Expected Value and Variance for 1090 Extended Squitter (ES) Aircraft Geometric Height

Aircraft geometric height can be obtained from the acquisition of 1090 data when an aircraft is transponding with an extended squitter. To derive the aircraft geometric height both the position message and the velocity message must be present and synchronized in time. The position message contains a rounded pressure altitude height and the velocity message contains the rounded difference between GPS height and pressure altitude height. For both the expected value and variance of the geometric height, the model considers that rounding could occur in one of three manners, the first is rounding up to the nearest 25 foot increment, followed by rounding to the nearest 25 ft increment and finally rounding down to the nearest 25 foot increment.

If we let d_r = round (GPS height – pressure altitude height)
h_{pa} = round (pressure altitude height)

It follows that the geometric height estimate of the aircraft from the extended squitter is

$$h_{es} = d_r + h_{pa}$$

Taking into account the random errors associated with the GPS measurement and pressure altitude measurement systems, we have

$$h_{gps} = h_t + e_n \qquad \text{where } h_t = \text{true geometric height of the aircraft}, \; e_n = \text{random error } N(0,\sigma)$$

and

$$h_{pa} = h_{pat} + e_{pa} \qquad \text{where } h_{pat} = \text{true pressure altitude of the aircraft}, \; e_{pa} = \text{random error } N(0,\sigma)$$

Taking into account the rounding errors in the system we can rewrite d_r and h_{pa} as

$$d_r = (h_t + e_n) - (h_{pat} + e_{pa}) + e_{rd} \qquad \text{where } e_{rd} = \text{difference rounding error } U[a,b]$$

and

$$h_{pa} = h_{pat} + e_{pa} + e_{rpa} \qquad \text{where } e_{rpa} = \text{pressure altitude rounding error } U[a,b]$$

hence the extended squitter geometric height of the aircraft can be rewritten as

$$\begin{aligned} h_{es} &= d_r + h_{pa} \\ &= (h_t + e_n) - (h_{pat} + e_{pa}) + e_{rd} + h_{pat} + e_{pa} + e_{rpa} \\ &= h_t + e_n + e_{rd} + e_{rpa} \end{aligned}$$

Letting $U[a,b] = U[0,25]$, then the data is always rounded up and the mean and variance of h_{es} can be expressed as

$$\begin{aligned} E(h_{es}) &= E(h_t + e_n + e_{rd} + e_{rpa}) \\ &= E(h_t) + E(e_n) + E(e_{rd}) + E(e_{rpa}) \\ &= E(h_t) + 0 + 12.5 + 12.5 \\ &= E(h_t) + 25 \end{aligned}$$

Which leads us to the true geometric height of the aircraft as

$$E(h_t) = E(h_{es}) - 25$$

And variance of h_{es} as

$$\begin{aligned} Var(h_{es}) &= Var(h_t + e_n + e_{rd} + e_{rpa}) \\ &= Var(h_t + e_n) + Var(e_r) + 2Cov((h_t + e_n), e_r) + Var(e_{rpa}) \\ &= Var(h_t + e_n) + Var(e_r) + 2[E((h_t + e_n)e_r) - E(h_t + e_n)E(e_r)] + Var(e_{rpa}) \end{aligned}$$

$$= \text{Var(GPS)} + 625/12 + 2E((h_t + e_n)e_r) - 2E(\text{GPS})(12.5) + 625/12$$
$$\sim \text{Var(GPS)} + 2E((h_t + e_n)e_r) - 25E(\text{GPS}) + 104$$

In the case when rounding is to the nearest 25 foot increment, the rounding error is defined on U[-12.5,12.5].

$$\begin{aligned}E(h_{es}) &= E(h_t + e_n + e_{rd} + e_{rpa}) \\ &= E(h_t) + E(e_n) + E(e_{rd}) + E(e_{rpa}) \\ &= E(h_t) + 0 + 0 + 0 \\ &= E(h_t)\end{aligned}$$

$$\begin{aligned}\text{Var}(h_{es}) &= \text{Var}(h_t + e_n + e_{rd} + e_{rpa}) \\ &= \text{Var}(h_t + e_n) + \text{Var}(e_r) + 2\text{Cov}((h_t + e_n), e_r) + \text{Var}(e_{rpa}) \\ &= \text{Var}(h_t + e_n) + \text{Var}(e_r) + 2[E((h_t + e_n)e_r) - E(h_t + e_n)E(e_r)] + \text{Var}(e_{rpa}) \\ &= \text{Var(GPS)} + 625/12 + 2E((h_t + e_n)e_r) + 625/12 \\ &\sim \text{Var(GPS)} + 2E((h_t + e_n)e_r) + 104\end{aligned}$$

In the case when rounding is down to the nearest 25 foot increment, the rounding error is defined on U[-25,0].

$$\begin{aligned}E(h_{es}) &= E(h_t + e_n + e_{rd} + e_{rpa}) \\ &= E(h_t) + E(e_n) + E(e_{rd}) + E(e_{rpa}) \\ &= E(h_t) + 0 - 12.5 - 12.5 \\ &= E(h_t) - 25\end{aligned}$$

$$\begin{aligned}\text{Var}(h_{es}) &= \text{Var}(h_t + e_n + e_{rd} + e_{rpa}) \\ &= \text{Var}(h_t + e_n) + \text{Var}(e_r) + 2\text{Cov}((h_t + e_n), e_r) + \text{Var}(e_{rpa}) \\ &= \text{Var}(h_t + e_n) + \text{Var}(e_r) + 2[E((h_t + e_n)e_r) - E(h_t + e_n)E(e_r)] + \text{Var}(e_{rpa}) \\ &= \text{Var(GPS)} + 625/12 + 2E((h_t + e_n)e_r) - 2E(\text{GPS})(-12.5) + 625/12 \\ &\sim \text{Var(gps)} + 2E((h_t + e_n)e_r) + 25E(\text{GPS}) + 104\end{aligned}$$

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