Altimetry System Error (ASE) Data Collection and Performance Monitoring
Topics for Discussion

• Data Elements and Issues
• Monitoring Methods
• AGHME Quality Control
• ASE Watch List
• Metrological Analysis
• RVSM Approval Database
DATA ELEMENTS AND ISSUES
Total Vertical Error (TVE)

- Total Vertical Error (TVE)
- Altimetry System Error (ASE)
- Flight Technical Error (FTE)
- Correspondence Error
- Assigned Altitude
- Deviation (AAD)
Elements of Total Vertical Error

• Total Vertical Error
  ✪ where an aircraft is in reference to the pressure altitude of the assigned flight level

• Displayed Altitude
  ✪ what the aircrew sees on the altimeter

• Transponded Altitude
  ✪ displayed altitude quantized (25 ft Mode S; 100 ft Mode C) is what TCAS and ATC see

• Altimetry System Error
  ✪ instrumentation error of the static source aircraft reference system is not typically seen unless using special instrumentation
Altimetry System Error Calculation Process

- Aircraft Position Data
  - Determine Aircraft Geometric Height
  - TVE (Total Vertical Error)
  - ASE (Altimetry System Error)
- Meteorological Data
  - Determined Flight Level (FL) Height
  - AAD (Assigned Altitude Deviation)
- Cleared FL
- Mode S or Mode C data
  - Compare Cleared FL to Assigned Altitude
  - ASE (Altimetry System Error)
Altimetry System Error (ASE) Risk

- Aircraft presumed level at FL350
- Aircrew observes aircraft level at FL350
- TCAS observes aircraft level at FL350
- Actual aircraft position in relation to observed FL – FL344
- Acceptable error tolerance level

ASE 600 ft.

Datablock indicates aircraft is level at FL350

- ASE is undetectable by aircrew, TCAS and ATC and has a marked effect on risk.

ATC Observes Aircraft Level At FL350
Baseline of the Height Monitoring

ASE Calculation

=> ASE (- 50ft)

AAD (~200ft)

TVE (~150ft)

Transponder Altitude

Assigned Altitude (FL)

Geom. Height Aircraft

Geom. Height FL380

Altitude / geom. height in ft

39000

38000

37000

19:50 19:52 19:54 19:56 19:58 20:00 20:02

Time
Monitoring Methods

- Height keeping performance of an aircraft is measured by equipment independent of the aircraft’s altimetry system.
- Aircraft must be airborne and operating at an RVSM altitude for the performance to be measured.
- Height keeping performance monitoring requires operators to use specialized monitoring systems.
Portable Monitoring System
GPS-Based Monitoring Unit (GMU)

- The GMU is a special-purpose data collection system carried aboard an aircraft, during which the unit collects Global Positioning System (GPS) pseudo ranges.

- Post-flight processing of these data ensures estimates of aircraft geometric height which are of sufficient accuracy to permit estimation of relevant height-keeping performance parameters. In parallel, the current-generation FAA GMU also collects secondary surveillance radar Mode C data, which also contributes to parameter estimation.

- The GMU has been in use since 1996 and has been used by thousands of operators to satisfy monitoring requirements associated with the State RVSM approval process.
Generations of GMUs

GPS Monitoring Unit
GMU – 1995

Enhanced GPS Monitoring Unit
EGMU - 2003

Enhanced² GPS Monitoring Unit
E²GMU - 2013

Total Number of GMU Monitorings as of 30 August 2016 = 19,260
GMU Monitoring Flights
Totals by Month/Weekly Average

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The William J. Hughes Technical Center has developed the ground-based Aircraft Geometric Height Measurement Element (AGHME) system as the principal means of satisfying one of the objectives of monitoring in connection with the North American RVSM.

These systems are positioned at fixed locations in the United States and Canada, automatically producing estimates of the geometric height of suitably equipped aircraft flying within the coverage area of an AGHME constellation.

Although intended to examine aggregate height-keeping performance, the AGHME system is entirely suited for the individual-aircraft monitoring which operators must complete as a part of the State RVSM approval process -- provided that the requirements for AGHME use are satisfied.
AGHME Locations & Percentages (2005- March 2016)

AGHME Locations in US and Canada

10 Million AGHME Measurements

- AACY: 20%
- ACLE: 8%
- AICT: 8%
- APDX: 4%
- APHX: 4%
- AYOW: 2%
- AYQL: 2%
- AYOW: 2%
- AYQL: 2%

Number of ASE Records seen by AGHMEs by State since 2005

Equipment
Ground Based Monitoring Systems …continued

**ADS-B Height Monitoring System**

**ADS-B Coverage Map as of October 2015**

**ADS-B Fields**

- Latitude
- Longitude
- Geometric Height
- Altitude
- Time
- Mode S Address
- Ground Station
- Flight Identification
- Navigation Accuracy Category

**2012 – February 2016 Data Sample for only DO-260 B Airframes**

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[Image of ADS-B Coverage Map]

[Image of ADS-B Fields Table]
AGHME QUALITY CONTROL
AGHME Quality Control (QC) Process

- Two primary sources of ASE measurement error must be evaluated before the result can be considered valid
  - Aircraft true position and the modeled value of the pressure surface
- Accepted quality parameters are built into the ASE processing software to flag likely erroneous ASE values
- Experienced analysts review ASE results periodically to identify remaining large ASE values
- QC has an established watch list of large measurement
  - Subsequent large measures of a single aircraft on repeated assessments are reported to the operators via the FAA inspector
  - Comparison of multiple aircraft at the same time or by area are used to remove the likely faulted measurement
Altimetry System Error (ASE) Process

- ASE is determined by comparing the identified true height of the aircraft and the true height of the barometric pressure surface associated with the altimetry measurement
  - The true altitude is currently measured by the Aircraft Geometric Height Element multilateration systems operated by ANG-E61
  - Aircraft that require ASE monitoring that do not fly over one of the AGHME sites can utilize a GPS measurement unit to collect aircraft position as an input to the ASE process
  - ADS-B provides a source of aircraft position data for use in ASE calculations
    - The quantity of data that will be provided by ADS-B will provide unprecedented ability to observe ASE
Flight Quality - Geometry

• For ASE to be properly measured by the AHGME, the geometry of the flight path should be aligned with the identified performance area of the system
• This assures that multiple elements of the AGHME station will measure the aircraft range for the altitude calculation
AGMHE Coverage Area: Wichita, Kansas

https://www.faa.gov/air_traffic/separation_standards/aghme/locations/
Recent AHGME Flight

Which ASE is correct?

ASE -101
SD 10
Segment 1

ASE 224
SD 123
Segment 2
Flight Segment 1 MARS Plot (Met/ASE Raw & Smoothed)

Well-sampled flight
444 Second Duration
Moderate MET/Aircraft surface agreement
Flight Segment 2 MARS Plot

- Poorly-sampled flight path
- 72 Second Duration
- Poor MET/Aircraft surface agreement
Pressure Surface Alignment
Sample Case with ADS-B

PHX
ASE 70
SD 42
Smoothed Height and MET Alignment

N40*, PHX, 11/29/15

Well-sampled flight
308 Second Duration
Moderate MET/Aircraft surface agreement
Smoothed Height and MET Alignment – ADS-B (MAARS)

Continuous ADS-B data aligned with AGHME data

Improved MET/Aircraft surface dynamic agreement

ADS-B ASE
Mean 114ft (70)
SD 11ft (42)
Flight Quality - Dynamics

• ASE is only currently processed when the aircraft is flying straight and level
  ✤ Maneuvers create uneven air flow over the aircraft
• A minimum flight segment of 3 minutes is required
  ✤ Multiple measurements during that time are averaged
  ✤ AGHME data is “geometrically limited” – the flight duration will only be as long as the flight distance over the system
  ✤ ADS-B coverage provides continuous data allowing for multiple independent ASE samples to be collected and compared.
Meteorological Data Quality

• Pressure Surface variation that do no match the expected model results will translate into erroneous ASE assessment
• Data evaluation based on the expected values of each site's performance can be used to detect bad MET fit
• A large standard deviation of the ensemble of site ASE measurement is used as a trigger for daily evaluation
  + The QC team can elect fail all or some of the data
Daily Statistics from Ottawa

An Elevated daily mean or standard deviation triggers QC data evaluation.
May 22, shown in orange, had a significantly lower ensemble bias that the prior and following days.
WATCH LIST AND LARGE ASE REPORTS
Analysis of ongoing height performance monitoring results has revealed that ASE can vary.

- Individual aircraft or an entire aircraft group

The need to establish an ASE independent monitoring program with a reporting process was identified.


The ASE-R assists the Federal Aviation Administration (FAA) and operators in identifying RVSM aircraft which exhibit unsatisfactory height keeping performance.
ASE-R Process

• NAARMO identifies aberrant performance for aircraft (ASE of 200 feet or greater).

• Aircraft placed on a watch list and identified as possible candidate for an ASE-R.
• NAARMO briefs Flight Standards on performance for the possible candidates for ASE-Rs.
• Team decides which are immediate candidates and presents findings to the Certificate Holding District Offices (CHDOs).
ASE-R Goals

- Educate all involved parties on the potential for large ASE existence ("invisible risk") and the risks associated with large ASE.
- Deliver a compelling case detailing why large ASE should be taken seriously and action should be taken immediately
- Improve aircraft performance
- Improve system safety
Altimetry System Error Report (ASE-R)

To: Operator Name
Operator Address

Prepared by: North American Approvals Registry and Monitoring Organization
Federal Aviation Administration
Atlantic City International Airport
Atlantic City, NJ 08405

Subject Aircraft Registration: N12345

Safe operation within Reduced Vertical Separation Minimum (RVSM) airspace requires stringent limits on the measurement of true aircraft altitudes during normal operations. Aircraft use a barometric altimeter to determine attitude and follow common pressure levels. Differences between the altitude indicated by the altimeter display and the actual pressure altitude corresponding to the undisturbed ambient pressure, known as altimetry system error (ASE). These errors are not apparent during flight operations. Therefore the altimeter displays to the aircrew and air traffic control a level that includes ASE. As such, the presentation to the pilot, ATC, and airborne collision avoidance systems is often different than the actual altitude of the aircraft. To be compliant with international standards, the ASE of an aircraft must be minimized and be no greater than 245 ft. Aircraft with observations of ASE greater than 245 ft in magnitude are candidates for removal of RVSM credentials and subject to immediate action.

Continued safe RVSM operations require a high level of accuracy from altimetry systems; therefore ongoing system performance monitoring as well as individual aircraft performance monitoring are necessary to ensure that safety goals and requirements are met. In order to support monitoring needs in accordance with international standards, requirements and recommended practices, the Federal Aviation Administration deployed six ground-based height monitoring units, also known as Aircraft Geometric Height Measurement Element (AGHME) systems, in the North American Region. These monitoring systems were strategically placed in high traffic flow areas and continuously record performance data.

The subject aircraft has been monitored by one or more AGHME systems and was found to exhibit large ASE values in magnitude greater than 200 feet. The William J. Hughes FAA Technical Center Quality Control Team in conjunction with the North American Approvals Registry and Monitoring Organization (NAARMO), tasked to provide Reduced Vertical Separation Minimum (RVSM) monitoring services to other Regional Monitoring Agencies (RMA) and State Authorities, cites ASE data collected in Tables 1-2 and Figures 1-4 as reason for safety concern.

Section I: Subject Aircraft and ASE Measurement Overview

Table 1. Aircraft Profile

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1. CAA Doc 6767A: "Manual on Implementation of a 200 ft (600 ft) Vertical Separation Minimum Between FL 290 and FL 410 Inclusive"

Figure 1 provides an overview of this aircraft's ASE performance at each AGHME element during a recent period.

Figure 1. Aircraft Altimetry System Error History

Table 2. Recent ASE Performance of Subject Aircraft

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Repealed AGHME Measurements for N12345
January 03, 2015 to March 07, 2016
Figure 2 provides a depiction of daily ASE observations from a single AGHME site on the day of the maximum observation of the subject aircraft.

Atlantic City AGHME Observations  
August 03, 2013

Figure 2. Atlantic City AGHME Observations Illustrating an Extreme Observation of the Subject Aircraft

Figure 3 is a comparison of the average ASE performance of aircraft of a similar type.

Average B737 ASE

Figure 3. Average B737 ASE for the Past Year

Figure 4 illustrates the probability (99.7%) that the ASE of a B737 aircraft will take a value within the expected range for this aircraft type.

Figure 4. Probability Density, B737 Aircraft

Section III: Continuing Maintenance Issues

During routine calibration, the aircraft systems are maintained on the ground while at rest, so the dynamic nature of ASE is not able to be seen. Aircraft altimetry systems also utilize parts that:
- wear over time (such as the pitot-static probe and portions of internal plumbing); and/or
- are subject to damage (such as skin flexing/deformation during operations); and/or
- are affected by modification of airframes (such as the application of paint, decals and branding marks or mounting of accessories or repairs such as sleeper plating in the vicinity of the static pressure ports).

Aircraft need to operate within RVSM limitations as published in the Aircraft Flight Manual (AFM). All these activities are capable of producing significant error in true height. Other factors seen in 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.

Section IV: Action Required

Because of this larger than normal or non-compliant value, it will be necessary to determine and remedy the cause or causes of non-compliant performance by the altimetry system and then repeat the monitoring process in order to demonstrate compliant performance. Prior to repeating the monitoring flight, the operator should ensure up-to-date compliance with the approved maintenance program, carefully inspect the aircraft altimetry system critical areas and review all relevant factors in order to determine any possible explanations for the observed ASE value.

Please complete the attached resolution form and submit to NAARMQ@fhsa.gov or fax to 609 485-5078 within 15 days or less of receipt of this report. Please note the aircraft’s altimetry system error must be corrected within thirty (30) days of FAA acceptance of the resolution plan.
ASE-R Resolution

• Upon completion of the corrective actions the aircraft RVSM height keeping gets reevaluated.
• A notice of resolution gets sent by the core team to the CHDO.
  ✦ This includes both positive and negative outcomes.
• Upon satisfactory review by the core team and the CHDO a decision is made to close the action on the ASE-R and the aircraft is removed from the watch list.
• If the maintenance leads to unsatisfactory performance, work is coordinated between all parties to continue to remedy the problems.
Altimetry System Error (ASE) Report
Resolution Sufficient

On August 26, 2016, the North American Approvals Registry and Monitoring Organization reported a large Altimetry System Error (ASE) for subject aircraft registration N12245 (report control number ASE-R XX). In the report data were presented demonstrating large ASE performance. A recommendation for maintenance review was advised to bring the ASE performance within RVSM compliant levels.

Upon further data inspection of the subject aircraft from recent AGIIME monitoring, the subject aircraft is now within RVSM compliant levels.

The following plot (Figure 1) indicates repeat ASE measurements before and after notification of large ASE performance.

Repeated Agime Measurements for A12245 (N12245)
January 6, 2015 to May 24, 2016

Figure 1
Conclusion

- This is an evolving process.
- Not all cases are the same.
- Working with Flight Standards has vastly helped in receiving the feedback needed to improve safety.
- While sometimes cost can be an issue, operators have been extremely helpful throughout the ASE-R process.
METROLOGICAL ANALYSIS
Meteorological Data (MET) Process

- Available Meteorological (MET) data is downloaded daily from the National Weather Service.
- MET data is processed by the ANG-E61 software tools using accepted models to determine the true altitude of barometric pressure surfaces.
- Additional automated processing matches a modeled pressure altitude surface with the location of an aircraft for ASE calculation.
- Mismatch of the modeled pressure surface and the actual pressure surface causes error in the ASE estimate.
Correction Between Pressure and True Altitude FL300
Meteorological Data Description
(Data Source is NOAA)

- To determine flight level height for the calculation of ASE, the FAA uses meteorological data from NOAA / NWS / NCEP / EMC (National Oceanic and Atmospheric Administration / National Weather Service / National Centers for Environmental Prediction / Environmental Modeling Center)
  - The EMC is one of nine National Centers for Environmental Prediction
  - The FAA uses the WAFS (Wide Area Forecast System) meteorological data file
  - The WAFS file is derived from the NCEP GFS (Global Forecast System)
- The atmospheric forecast model the GFS uses is the GSM (Global Spectral Model) with spherical harmonic basis functions
  - The initial conditions the GSM uses is from the NCEP GDAS (Global Data Assimilation System)
- The GDAS uses all satellite, conventional, and radar observations within a plus or minus 3 hour window of the analysis time
- The NCEP Unified Post Processor (UPP) compares and verifies all model output
Flight Level Height Estimation
(Flight Levels Are Pressure Surfaces)

- Aircraft fly and maintain altitudes by measuring meteorological pressure levels defined by the Standard Atmosphere
- For each RVSM flight level [290 – 410] there is a corresponding mb level (pressure surface) that is defined by the Standard Atmosphere
  - For example, when an aircraft is assigned FL290 (29,000 feet), the aircraft avionics / pitot static system will try to measure a mb level of 314.94911 as defined by the Standard Atmosphere
Pressure Surface

let $p_{1_i} = \text{standard atmosphere mb levels}$
   = \{400, 300, 250, 200, 150, 100\}, i = 1, \ldots, 6

$h_{1_i} = \text{standard atmosphere geopotential heights (feet) at mb levels } p_{1_i}$
   = \{23574.2, 30065.4, 33999.1, 38661.3, 44646.8, 53082.8\}

$h_{2_j} = \text{standard atmosphere geopotential flight levels heights}$
   = \{29000, 310000, \ldots, 45000\}, j = 1, \ldots, 9

$p_{2_j} = \text{standard atmosphere mb levels at } h_{2_j} \text{ flight level heights}$
   = \{314.84911, 287.44595, 262.00689, 238.42236, 216.62475, 196.77083, 178.73656, 162.35514, 147.47510\}

$h_{3_j} = \text{WAFS geopotential heights at mb levels } p_{1_i} \text{ (input variable)}$

$t_i = \text{WAFS temperatures at mb levels } p_{1_i} \text{ (input variable)}$

$t = \text{mean WAFS temperatures between mb levels (estimated variable)}$

$t_1 = \text{mean WAFS temperatures between mb levels and flight level (estimated variable)}$

$h = \text{geopotential flight level height (estimated variable)}$

let $d = (t_{i+1} - t_i) / (h_{1_{i+1}} - h_{1_i})$

$t_1 = t_i + (d/2) (h_{2_j} - h_{1_i})$

$r = \ln(p_{1_i}/p_{2_j}) / \ln(p_{1_i}/p_{1_{i+1}})$

$d_1 = (t_1 / t_i) r$

then

$h = h_3 + d_1 (h_{3_{i+1}} - h_{3_i})$
RVSM Approval Requirement

• In order to ensure that the overall safety objectives of the air traffic services (ATS) system can be met, all aircraft operating in airspace where RVSM is applied are required to hold an approval, issued by the State of the Operator or State of Registry as appropriate, indicating that they meet all the technical and operational requirements for such operations.

• The specific aircraft type or types that the operator intends to use will need to be approved by the State of Registry of the aircraft or of the aircraft operator.

• RVSM approval issued for one region will always be valid for RVSM operations in another region provided specific restrictions have not been imposed on the operator by the State of the Operator or State of Registry.

• This requirement, and the responsibility of States with regard to the issuance of these approvals, are specified in 7.2.4 b) of Annex 6, Parts I and II.
RVSM Approvals Database

- One of the functions of an RMA is to establish a database of aircraft approved by its State authority for operations in RVSM airspace in the region for which the RMA has responsibility.

- This information is necessary for two reasons:
  a) the RMA is responsible for verifying the approval status of all aircraft operating within its region; and
  b) height-keeping performance data must be correlated to an approved airframe.

Reference: ICAO Doc 9937, paragraph 2.1.1
RVSM Approval Elements

• RVSM approval will encompass the following elements:
  
  a) Airworthiness approval (including continued airworthiness). The aircraft will be approved as meeting the requirements of the appropriate State airworthiness document derived from the height-keeping capability requirements as defined by the RVSM MASPS [Minimum Aviation System Performance Standard]. Furthermore, the aircraft altimetry and height-keeping equipment must be maintained in accordance with approved procedures and servicing schedules; and

  b) Operational approval. As defined by ICAO regional air navigation agreements, it may be necessary for an operator to hold a separate RVSM-specific operational approval in addition to an RVSM airworthiness approval to operate in RVSM airspace.

Reference: ICAO Doc 9574, paragraph 3.3.1
RVSM Approvals Data Collection

• An RMA serves as a focal point for the collection and collation of RVSM approvals for aircraft operating under its jurisdiction.

• To avoid duplication by States in registering approvals with RMAs, all States are associated with a particular RMA for the processing of RVSM approvals.

• Links with other RMAs are established in order to determine the RVSM status of aircraft it has monitored, or intends to monitor, so that a valid assessment of the technical height-keeping risk can be made.

Reference: ICAO Doc 9937, paragraphs 2.2.1, 2.2.3
RVSM Approvals Database Requirements

- To properly maintain and track RVSM approval information, some basic aircraft identification information is required (e.g. manufacturer, type, serial number, etc.) as well as details specific to an aircraft’s RVSM approval status.

- There are frequent changes to aircraft registration data. Changes to registration and/or operating status data are required to properly maintain an accurate list of the current population as well as to correctly identify height measurements.

- An accurate and up-to-date list of contacts is essential for an RMA to do business.
  - State Airworthiness Officials
  - Operators
  - Manufacturers

Reference: ICAO Doc 9937, Appendix D, paragraphs 1, 2 and 3
Minimum Aviation System Performance Standards (MASPS) Database

- The FAA Separation Standards Branch maintains the Minimum Aviation System Performance Standards (MASPS) database to support the Reduced Vertical Separation Minimum (RVSM) program, and the North American Approvals Registry and Monitoring Organization (NAARMO), which is the ICAO endorsed Regional Monitoring Agency (RMA) for North America.

- NAARMO performs analysis of RVSM aircraft and operator approvals: evaluates operations specification approvals, letters of authorization, validity of registration information, and height monitoring compliance.

- Currently the total population of US registered aircraft is 319,946, of which 22,135 are involved in the RVSM program.

- NAARMO shares approvals and monitoring information with the other Regional monitoring agencies (RMAs). Data is also uploaded to the ‘US RVSM Approvals and AGHME Monitoring Status Results’ website on a monthly basis, from this output FAA Inspectors and aircraft operators are able to view the RVSM approval and height monitoring status of an aircraft.
## US RVSM Approvals and AGHME Monitoring Status Results

Sample from:

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RVSM Database Entry Tool