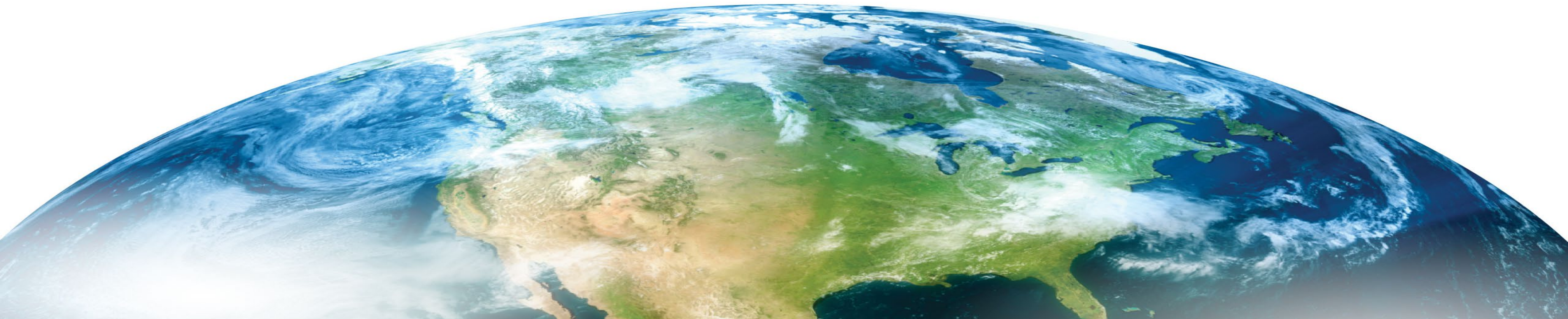
ADS-B Height Monitoring in the USA

September 2023

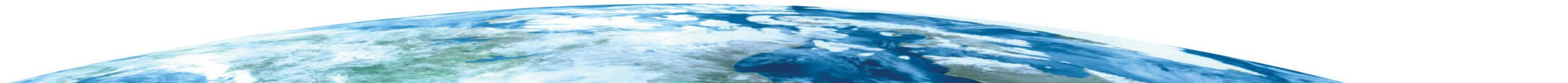


Safety Objectives of the RVSM Monitoring Program

The Manual on a 300 m (1000 ft.) Vertical Separation Minimum Between FL 290 and FL 410 Inclusive (Doc 9574) states:

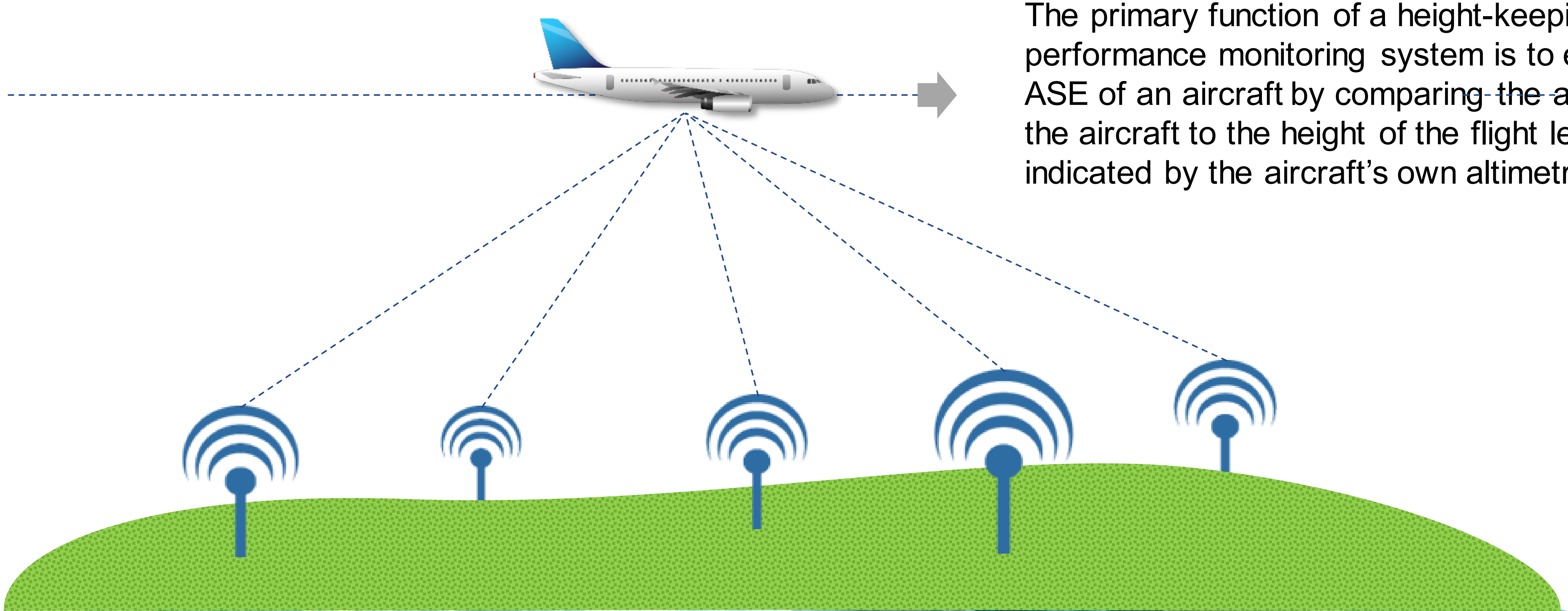
- ✓ Verification that the target level of safety will be met upon implementation of RVSM and will continue to be met thereafter
- ✓ Monitoring of the effectiveness of the altimetry system modifications which have been implemented to enable aircraft to meet the required height-keeping performance criteria
- ✓ Evaluation of the stability of altimetry system error (ASE)

Consequently, oversight bodies termed Regional Monitoring Agencies (RMAs), were established world-wide.



Height-Keeping Performance Technical Objectives

An RMA should design a height-keeping performance monitoring program to provide ongoing summary information of ASE performance by aircraft-type group so that adverse trends can be identified quickly.



The primary function of a height-keeping performance monitoring system is to estimate the ASE of an aircraft by comparing the actual height of the aircraft to the height of the flight level as indicated by the aircraft's own altimetry system.

Separation Standards Analysis Program Performance Monitoring

SEPARATION STANDARD DEVELOPMENT

- ✓ Separation and airspace concepts assessed in analytical and modeled environments to determine the safety of operations, technical and operational performance suitability, and usability.

PERFORMANCE MONITORING

- ✓ **Independent ASE RVSM monitoring**
- ✓ **ADS-B ASE monitoring**
- ✓ **Post-implementation monitoring of RNP/ RNAV performance-based navigation routes**

SAFETY ANALYSIS

- ✓ Safety management system (SMS) oversight & reporting
- ✓ Collision risk modeling
- ✓ Conformance monitoring

RISK ASSESSMENTS

- ✓ Operational data collection and analysis
- ✓ Hazard identification
- ✓ Risk mitigation

MONITORING AGENCIES

- ✓ Operates three monitoring agencies serving the North American and Pacific Regions
- ✓ North American Approvals Registry and Monitoring Organization (NAARMO)
- ✓ Pacific Approvals Registry and Monitoring Agency (PARMO)
- ✓ Pacific Enroute Monitoring Agency (EMA)

FAA Monitoring Methods

GPS-based Monitoring Unit (GMU) – a portable device brought on board and operated by trained technicians. This method uses GPS data to collect the aircraft's position that is then used in the ASE process. **Over 21,000 flights** were monitored using this method from 1995-2023.

Aircraft Geometric Height Measuring Element (AGHME) – with this method, the true altitude is currently measured by the ground-based AGHME multilateration technique systems operated by the FAA. **Over 14.5 million** AGHME measurements using this ground based monitoring system from 2004-2023.

Automatic Dependent Surveillance-Broadcast (ADS-B) Height Monitoring System (AHMS) – provides a source of aircraft position data for use in the ASE calculations. Over **200 Million 5-minute** ASE samples have been collected from 2019-2023

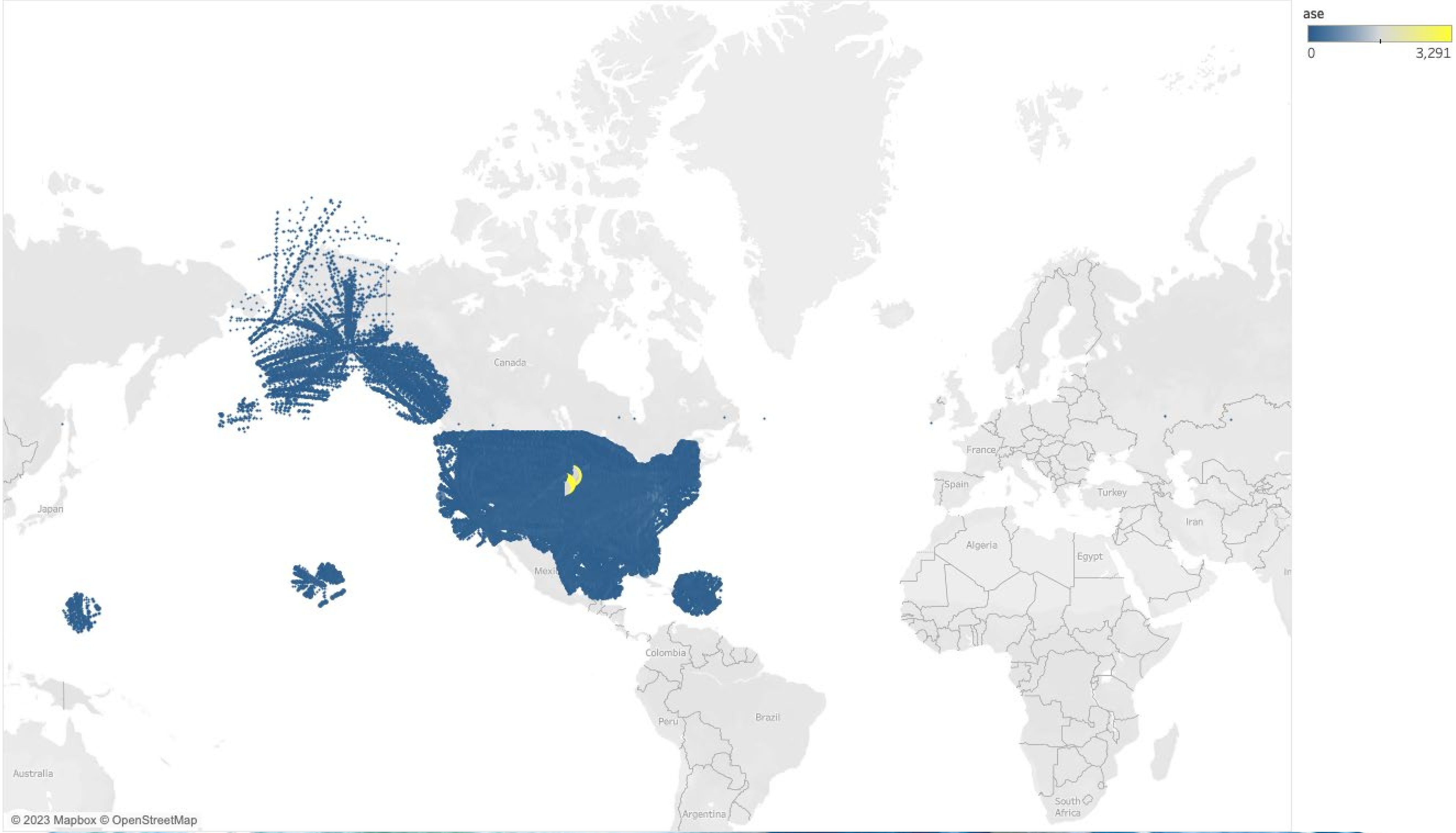
FAA Advisory Circular 91-85B – 01/29/2019*

E.1.4 How Do I Get My Airplanes Monitored?

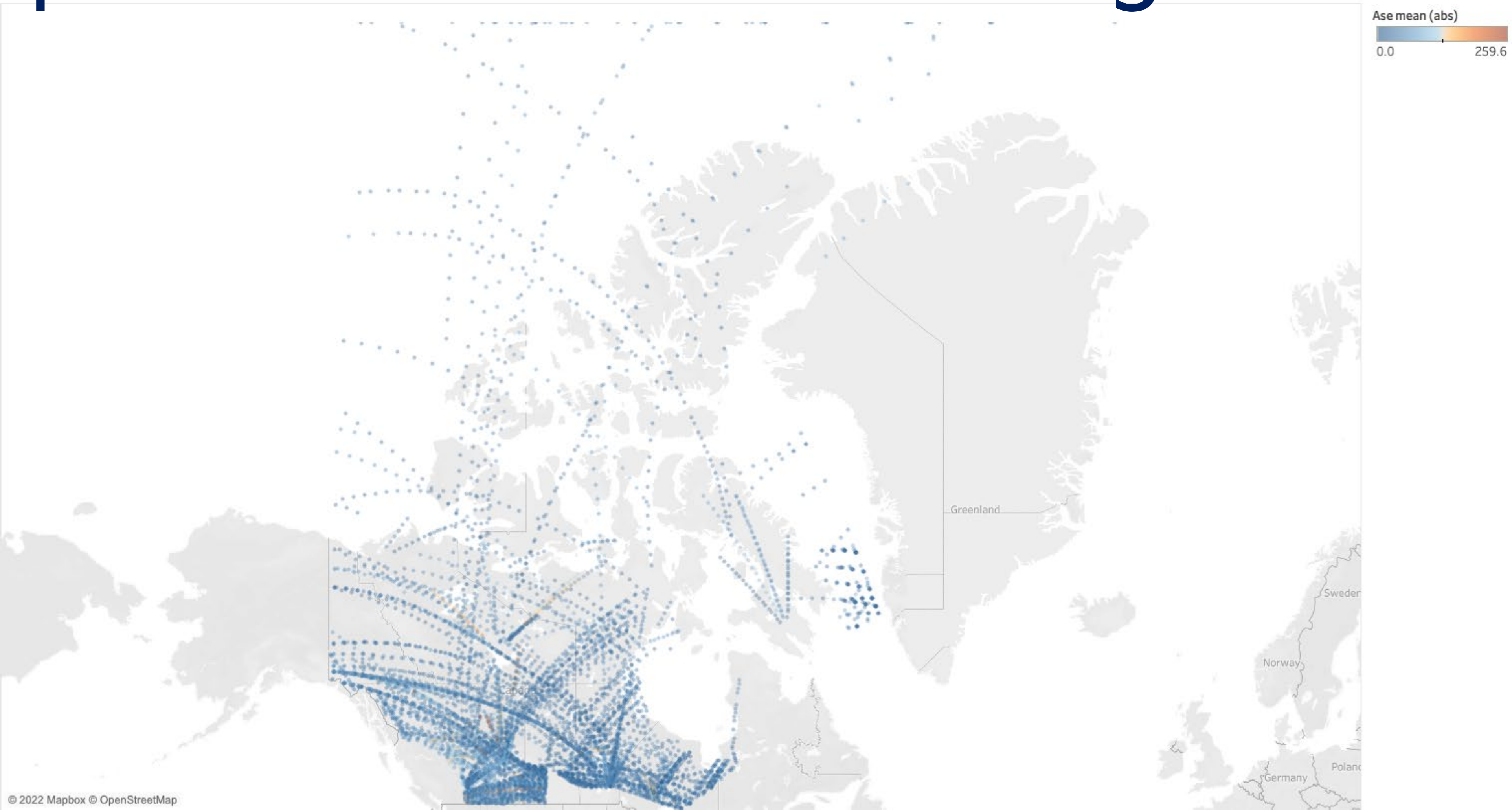
1. An operator may choose to fly with a trained technician from an FAA-approved RVSM monitoring support provider utilizing a GMU on board the airplanes.
2. An operator may fly an airplane through an established ground-based height-measuring system. Currently, ground-based systems exist in:
   - North America, AGHME (requires Mode S equipment); or approved ground-based height-measuring systems in other regions (e.g., Europe or Japan).
   - An RVSM-authorized aircraft equipped and operating with ADS-B OUT avionics meeting the performance requirements of part 91, § 91.227 at an RVSM altitude where ADS-B height-monitoring is provided.

* ADS-B ASE monitoring was included in AC 91-85A 07/21/16

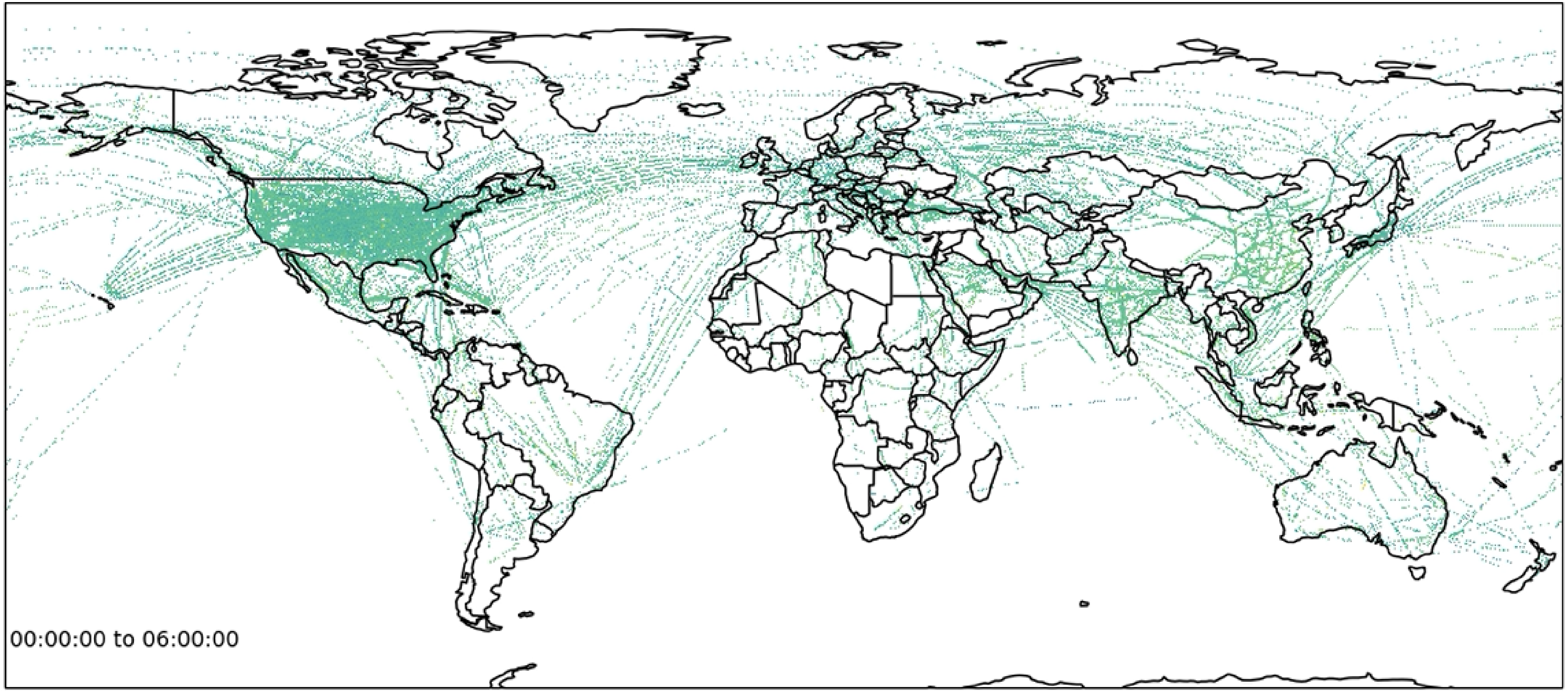
Scope of ADS-B ASE Monitoring - US



Scope of ADS-B ASE Monitoring - Canada



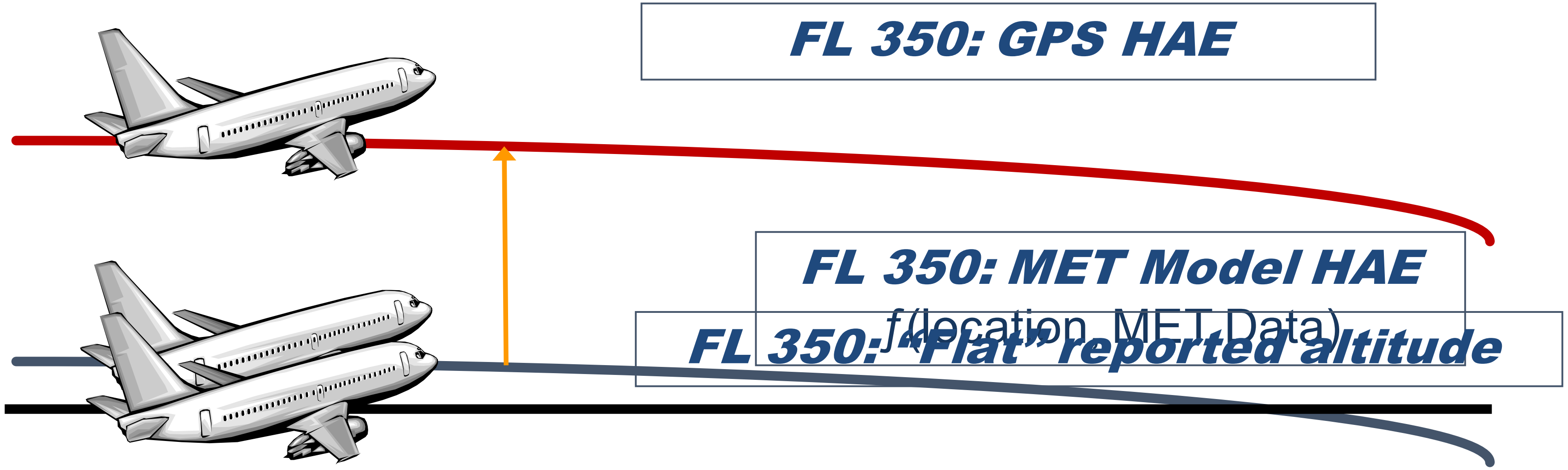
FAA Space-Based ADS-B Testing



ASE Calculation Details

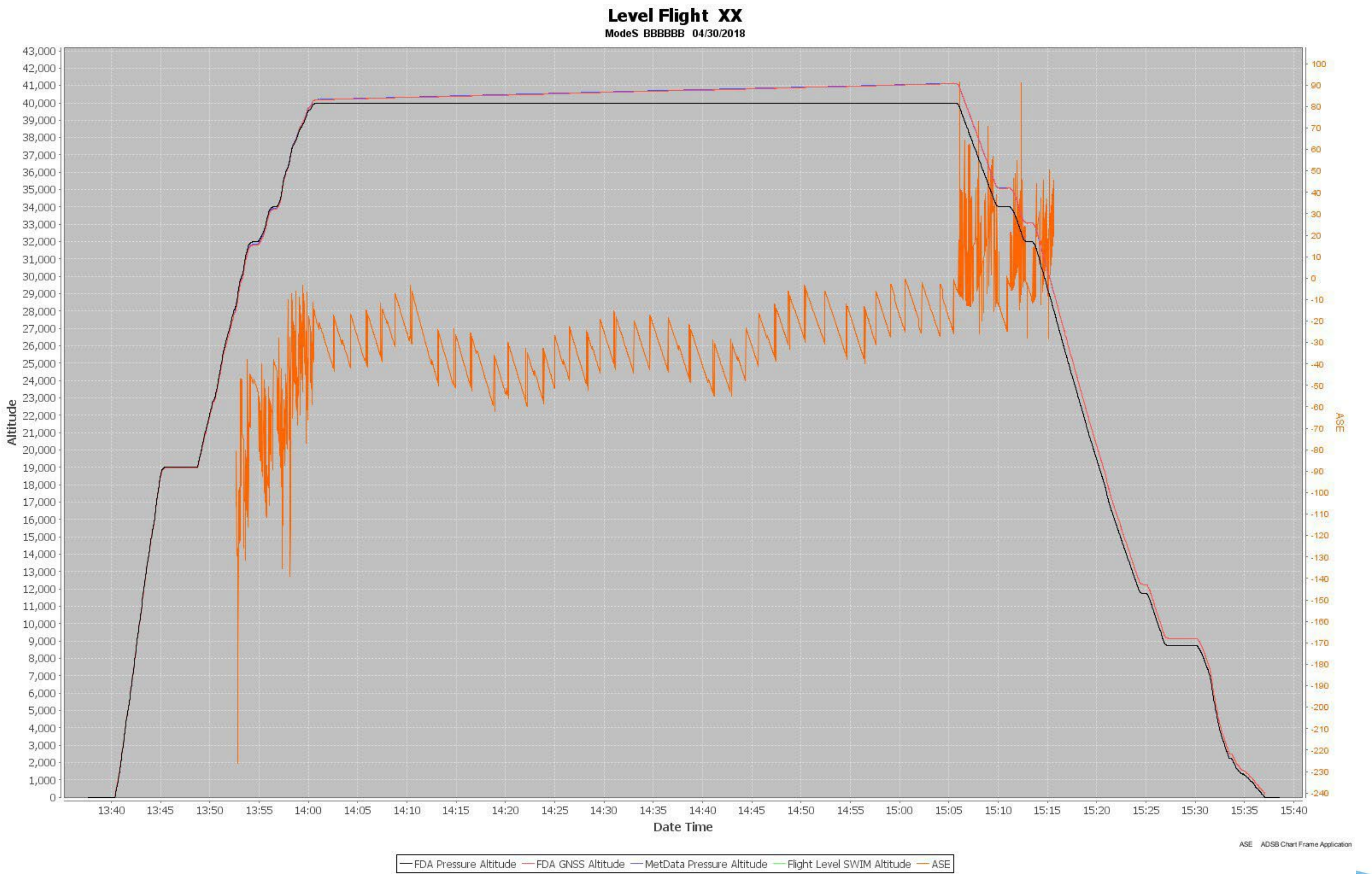
- Altimetry System Error (ASE) is determined by comparing the identified geometric height of the aircraft and the geometric height of the barometric pressure surface associated with the altimetry measurement
  - Automatic Dependent Surveillance- Broadcast (ADS-B) Out provides a source of aircraft position data for use in ASE calculations
  - Necessary Meteorological (MET) data is downloaded daily from the US National Oceanic and Atmospheric Administration (NOAA) and the National Centers for Environmental Prediction (NCEP) website

ASE Illustration

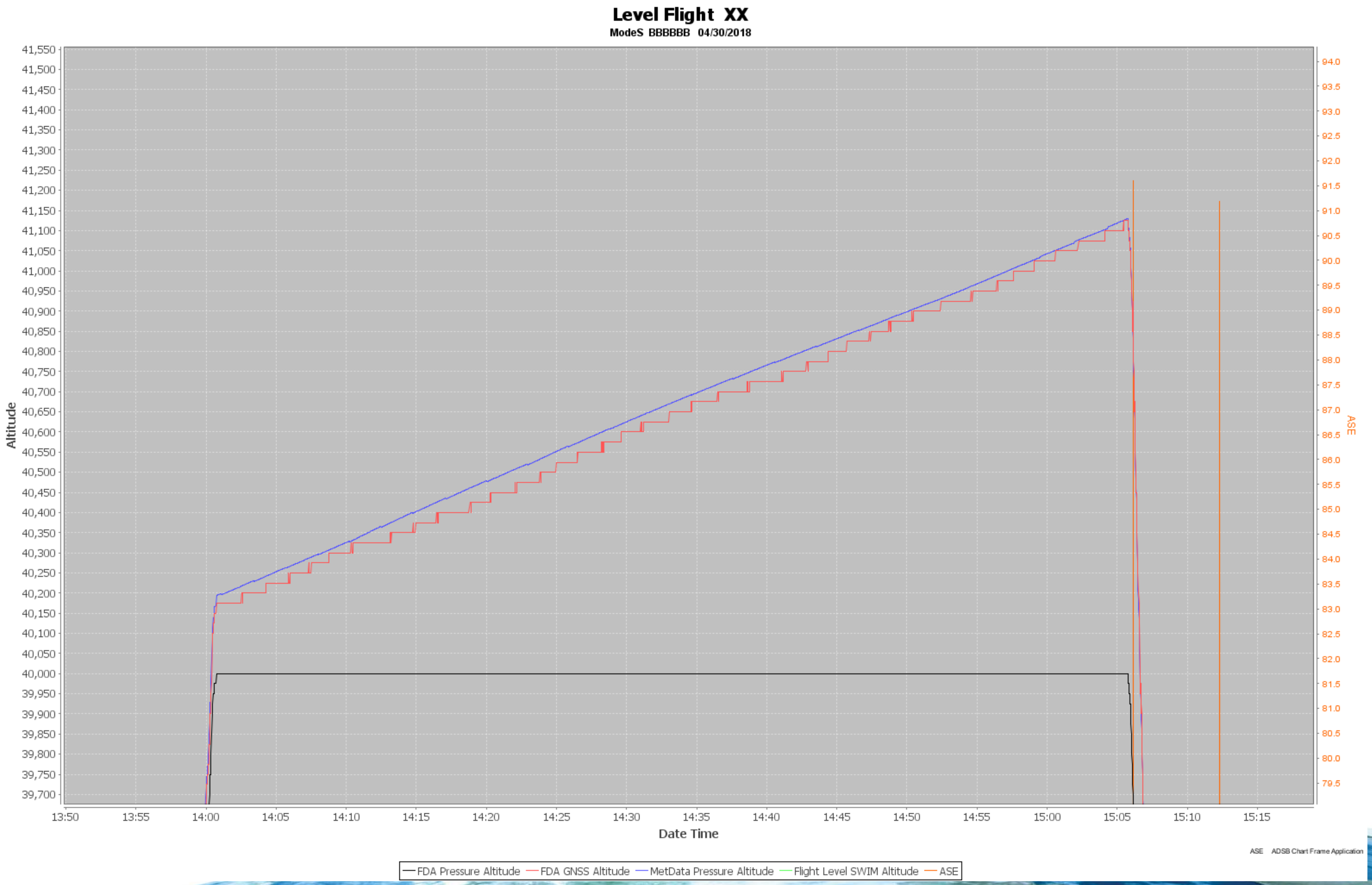


ASE = GPS HAE – MET Model HAE

Data Visualization – Full Flight



Data Visualization – Zoom to Altitude Data

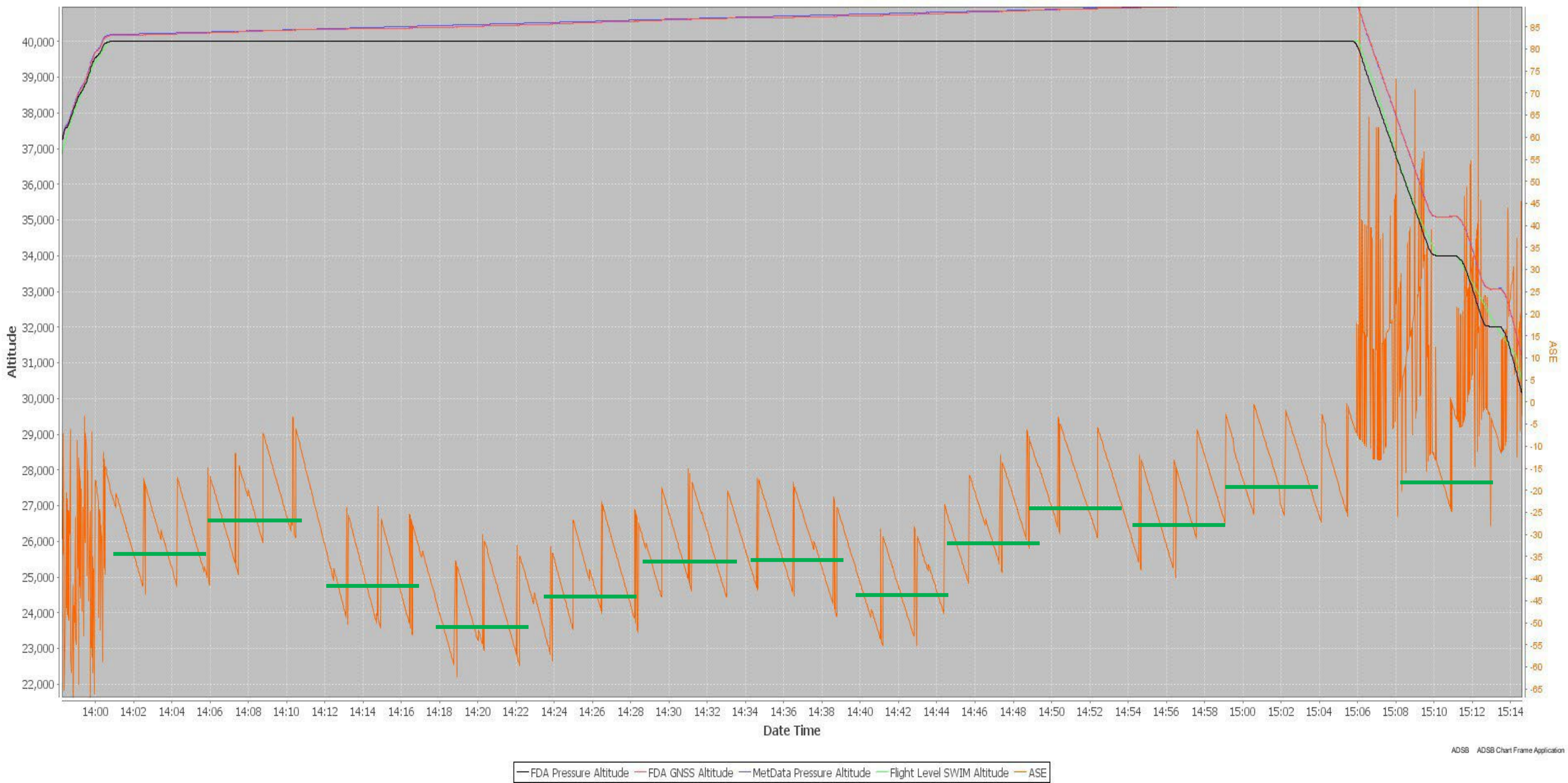


This graph depicts aircraft altitude-keeping information using ADS-B Out.

- The aircraft is maintaining FL400 (reported pressure altitude) (black line, left scale
- The blue line is the modeled meteorological data
- The red line is the GPS reported altitude

This aircraft is on its cleared flight level.

ASE Samples: 5-minute Averaging



Removing ADS-B Resolution Noise

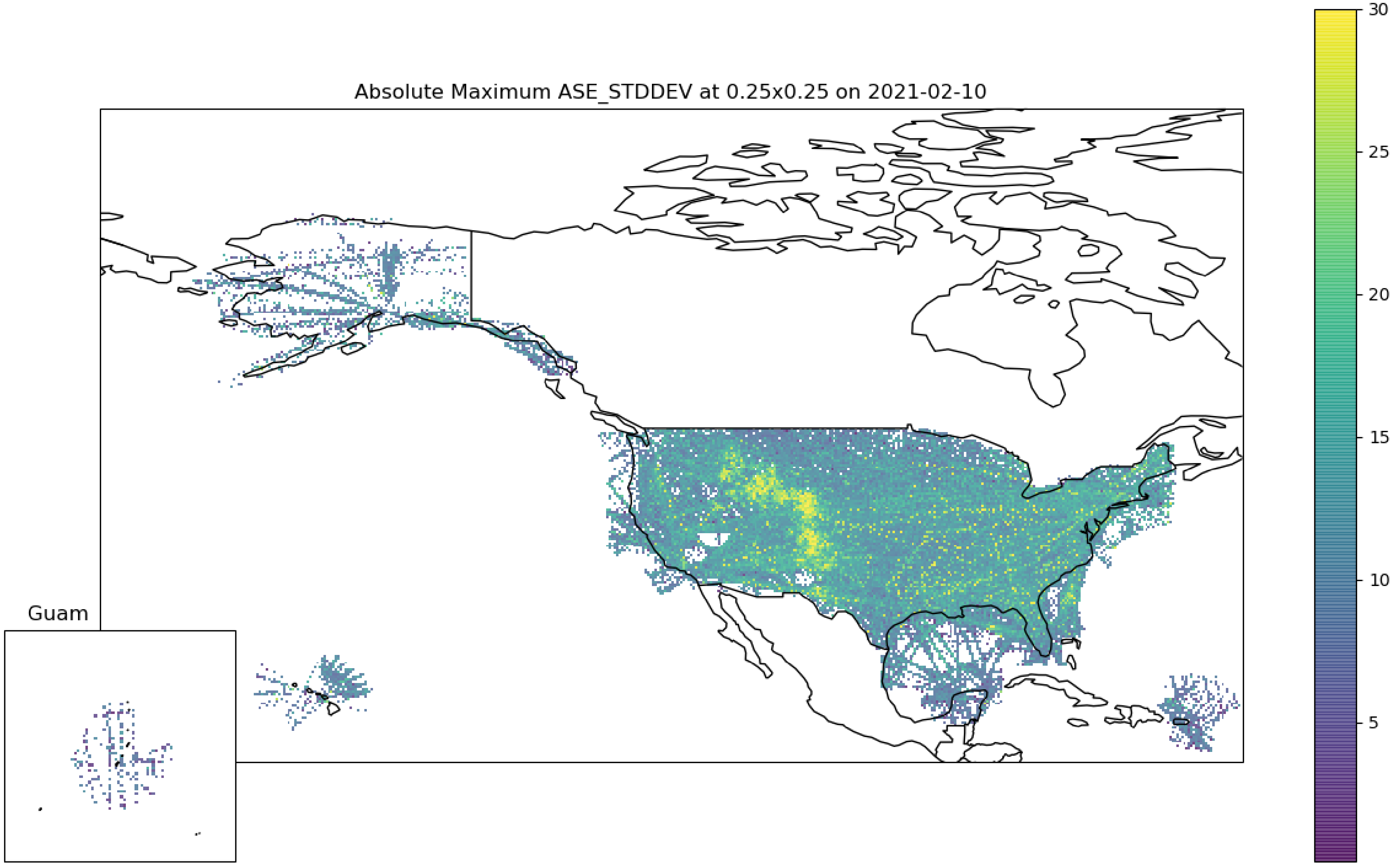
- Both Mode-S pressure altitude and GPS altitude are rounded to the nearest 25ft in the ADS-B broadcast
  - Altimetry systems attempt to maintain a constant FL while the actual height above the ground changes
    - Constant pressure data fed into the MET model produces a smooth function
  - Quantized GPS height data creates a saw tooth function in the ASE profile
- ASE is averaged over 5 minute segment to determine one ASE sample

Quality Control

- Quality Control of the ASE input data includes:
  - GPS solution accuracy parameters
    - ADS-B provides several GPS solution quality factors representative of horizontal solution quality that can be used for removing suspected poor GPS data
    - Geographic performance plots can also provide an indication of poor solution quality
  - MET anomaly detection
    - Storms, turbulence, large pressure gradients will also cause errors in the ASE results
    - Includes identification of areas where the MET model frequently has large mismatches with multiple aircraft

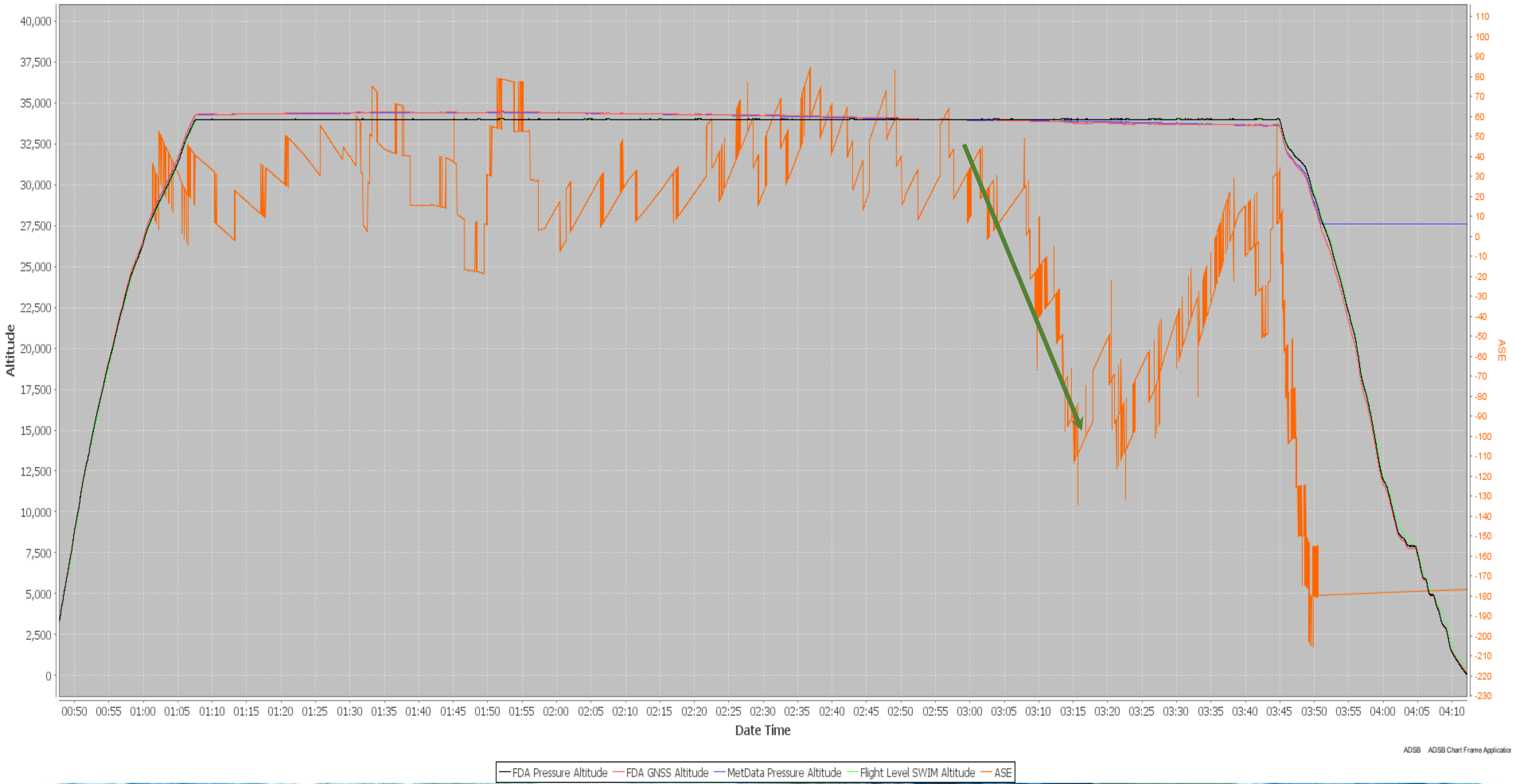
Significant Terrain Features in the United States

ASE Standard Deviation and Terrain



ASE Quality Control

Large ASE Anomaly – Change of 180ft in 25 minutes



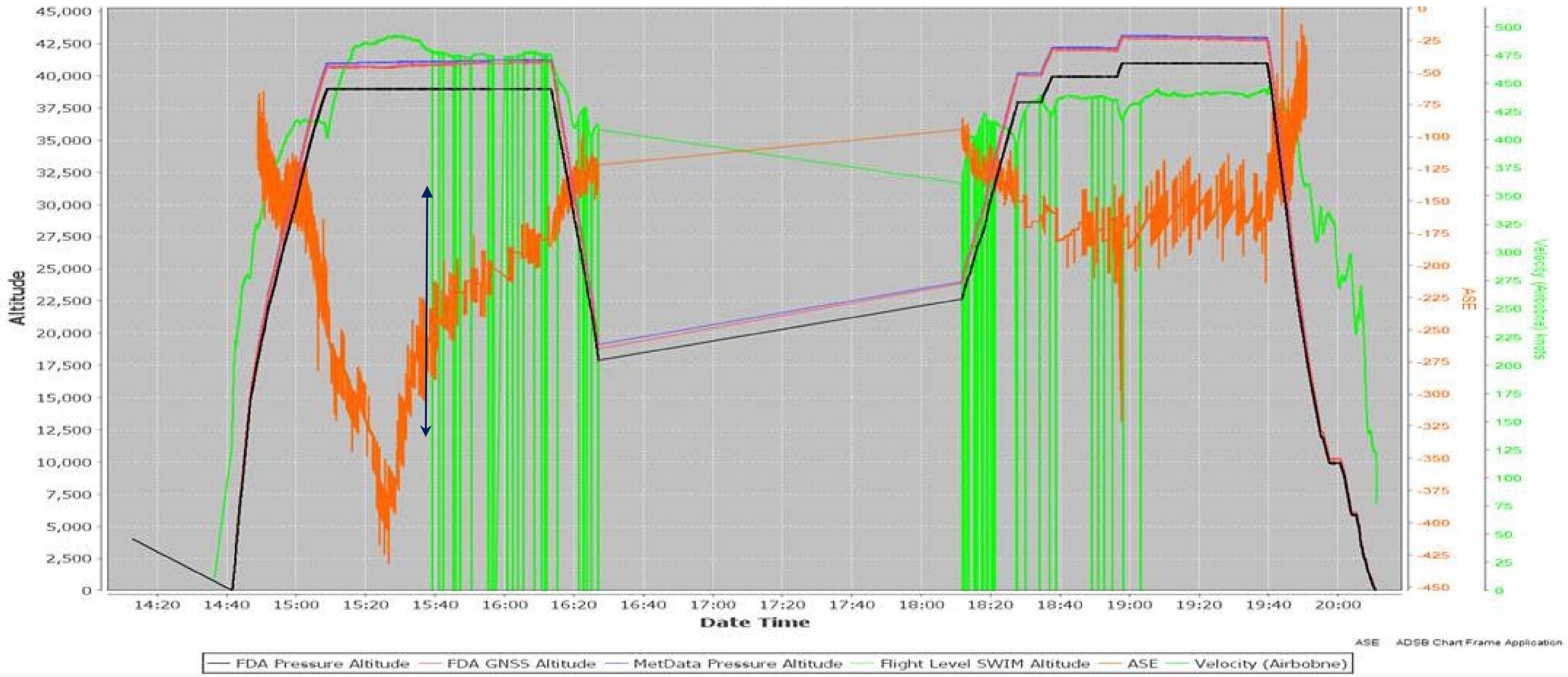
ASE Quality Control

ASE Anomaly – Large GPS Position Offsets from the MET Model
GPS or MET Issue?

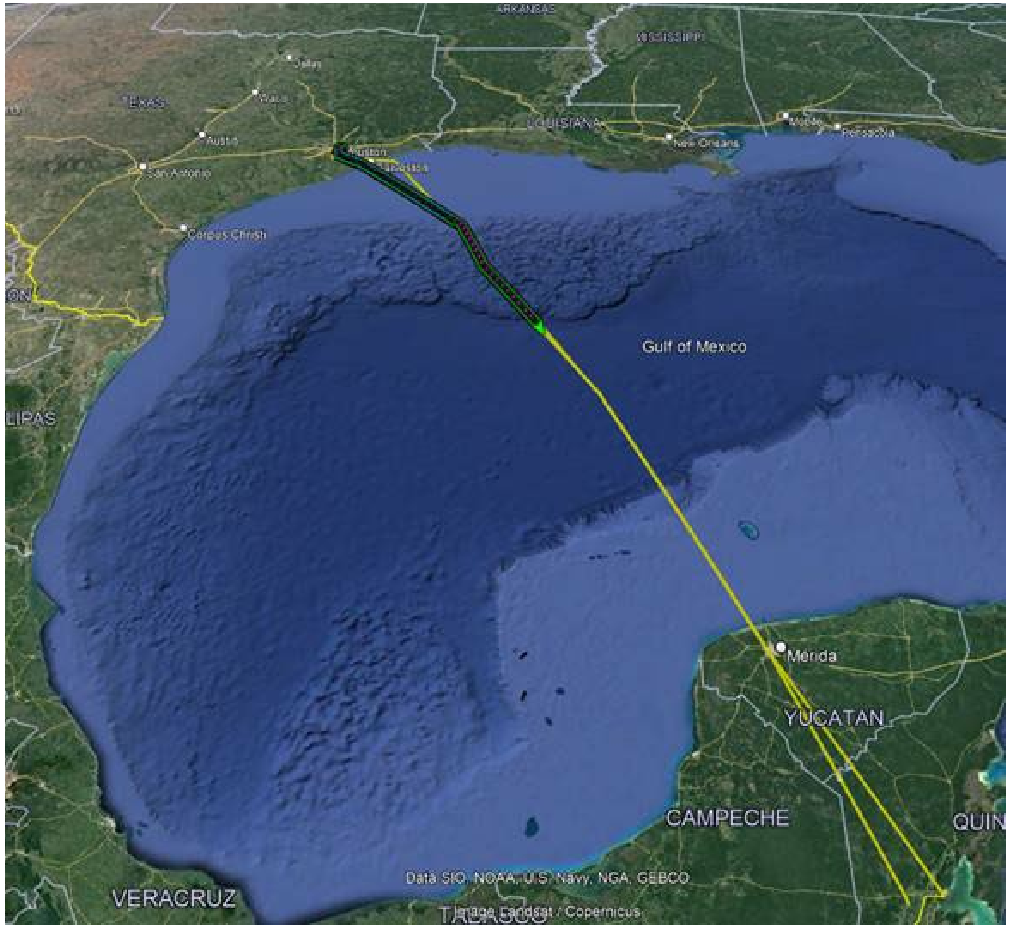
ASE Quality Control

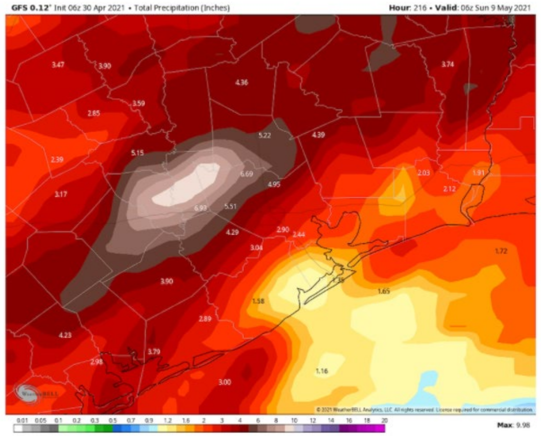
Position of the anomaly suggests Mountain Wave Effects

MET Anomaly Caused by a Storm

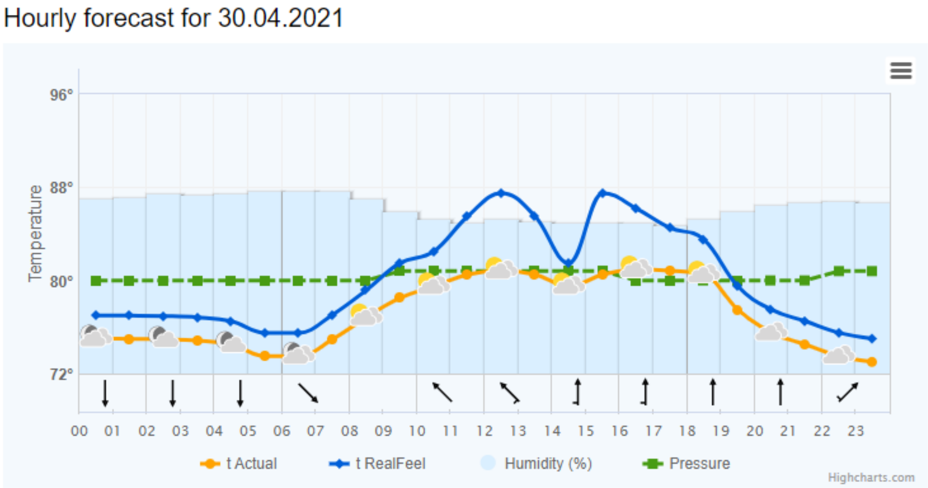


Ground Track of Flight and MET

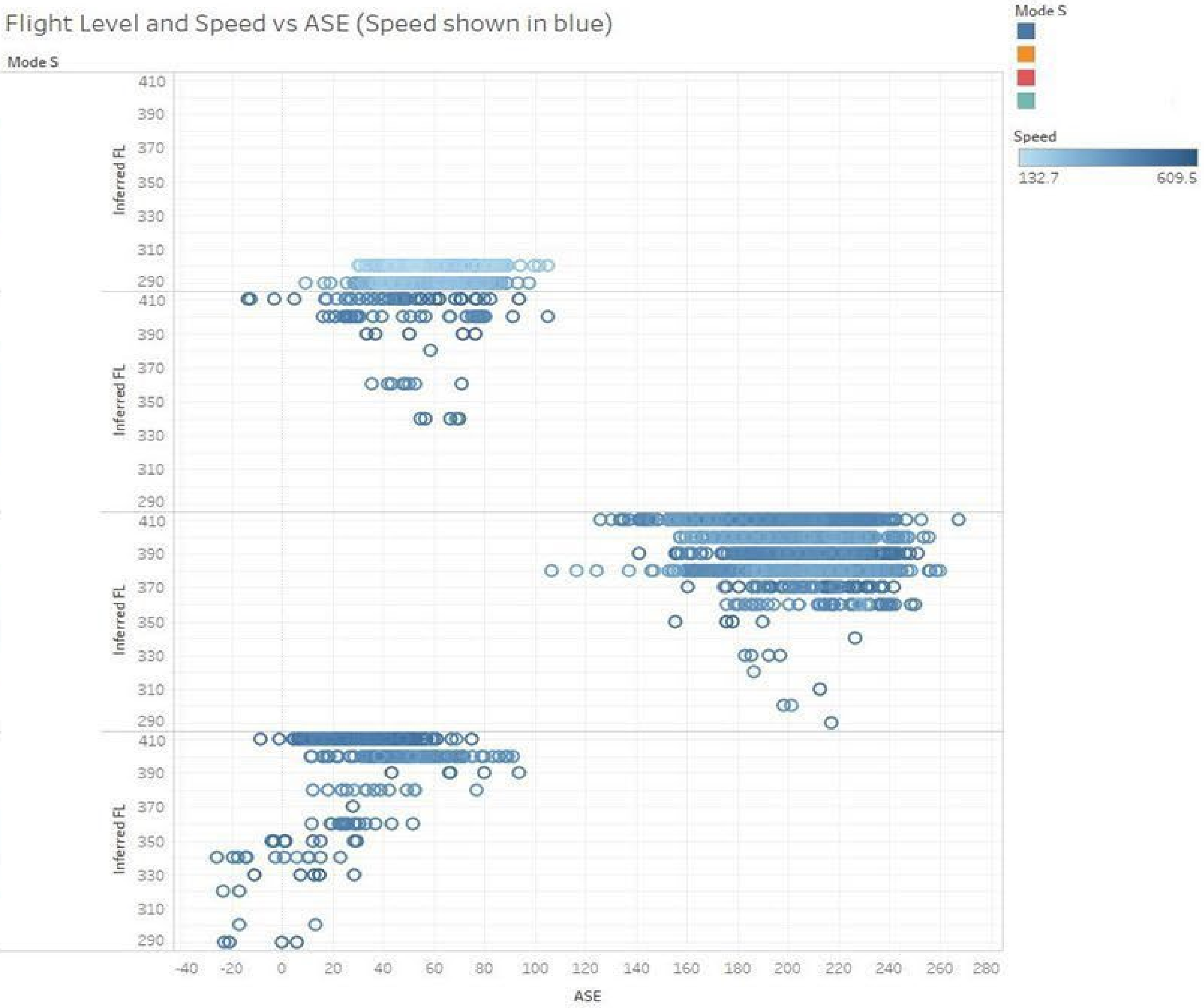




The American GFS model simulates rainfall in Houston through Sunday. (WeatherBell)

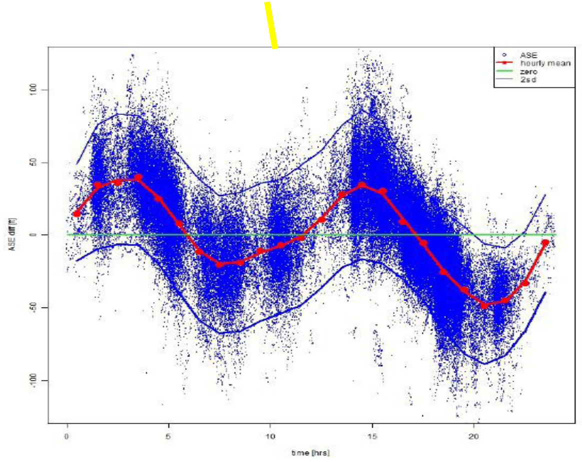


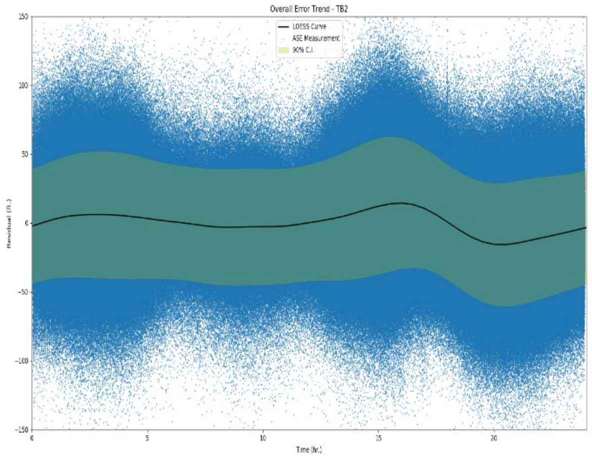
Sample Database Output: Operator Report with Poor Performer

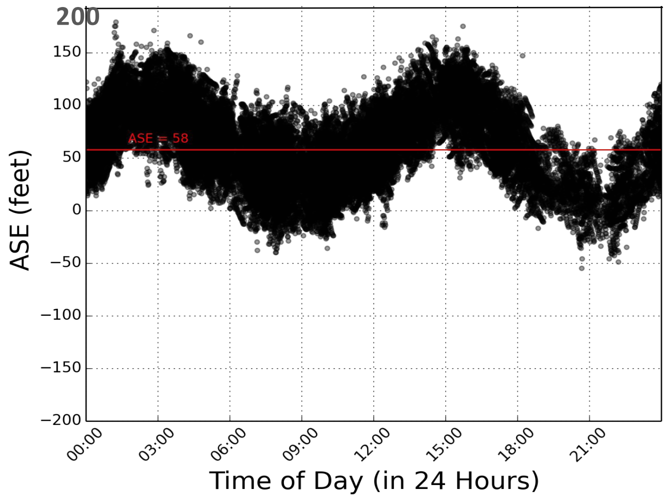


Additional MET Analysis is needed

- RMAs have observed a time-of-day bias in the process ADS-B ASE results
  - The likely source is the MET data, however, additional work is needed to identify the source and remove the bias







Benefits of Frequent Monitoring

- Daily monitoring of all flights within US airspace supports any flights required for Section 9 operators to be initially monitored
- Uncertainty in the ASE estimates due to observed errors in the current MET data are averaged over time. More ASE observations reduce uncertainty in the ASE average
- Minimum monitoring requirements are easily met with regular ADS-B ASE processing
  - Detection of faulted aircraft is simplified with more observations

Additional Uses for ADS-B data (1)

- Risk Analysis:
  - Mandatory Error Reports are written narratives of operational events. These reports contain estimates of the event characteristic. ADS-B trajectory data can be used to directly validate MOR descriptions
  - TCAS Resolution Advisories are not considered risk bearing events when the crew correctly follow with RA
    - Evaluation of the TCAS instruction compared with the event trajectories can identify cases where the RA were not properly executed
      - Incorrect vertical direction, horizontal deviation, continued vertical deviation after the RA is terminated

Additional Uses for ADS-B data (2)

- Design Certification
  - RVSM designed currently can be verified by one of three methods:
    - Trailing Cone data collection
    - Precision Radar
    - Calibrated chase plane
  - Requires specific testing of all points in the design envelope
- ADS-B ASE processing can analyzed during all phases of an overall aircraft design flight test program, incorporating, as needed, any cases necessary for the RVSM design approval without the need for additional equipment

Summary

- Availability of aircraft position data in ADS-B messages provides an unpresented ability to observe ASE
- Accuracy of ADS-B ASE processing will be improved with additional work to identify and resolve identified bias
- Data quality control is an essential part of the any aircraft analysis to be sure the ASE is a true measure of the system performance

Questions ?

Extra Slides

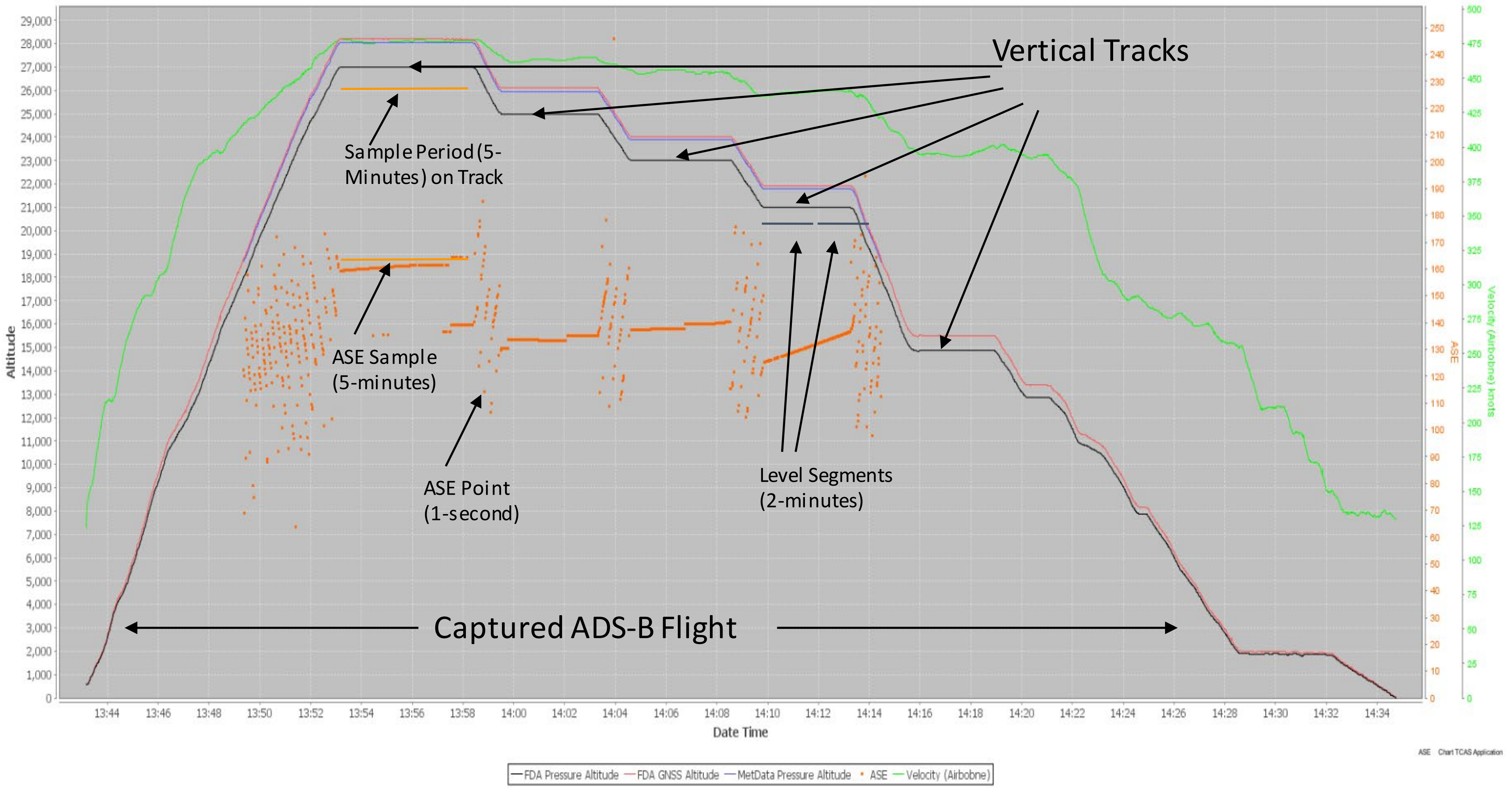
- ADS-B ASE Processing

ASE Processing Naming Conventions

- ADS-B Data Definitions
  - A **Flight** is a full period of ADS-B data from take-off to landing
  - A **Level Segment** is a period of time when an aircraft appears to be maintaining level flight at an assigned altitude
  - A **Vertical Track** is a sequence of continuous Level Segments
  - An **ASE Sample** or **Sample** is a 5-minute section of a vertical track used for ASE averaging
  - An **ADS-B Data Point** is one instantaneous sample of ADS-B data
  - A **Flight Level** is an assignable integer pressure altitude (FL310)

- A flight may have one or several Vertical Tracks
- Each Vertical Track is broken down into an integer number of ASE Samples
  - A 37-minute **vertical track** would produce seven 5-minute **samples**
- Any **sample** may have from 1 to 300 **points**

Typical Flight Vertical Profile



Pre-Process Meteorological & Geoid Data

- Download Meteorological Data from NOAA
  - Convert MB Levels to Flight Levels (FL 180 – FL 670)
- Convert Geopotential Heights to Height Above Ellipsoid (HAE) for the Meteorological data
  - Verify current Gravitational Earth Model is correct
    - Source location for the geoid:
      [NGA - Office of Geomatics Home Page]
- Interpolate the Meteorological Data with respect to the Date, Time, Latitude, Longitude, and Pressure Altitude of the aircraft to be assessed.
  - MET data Altitude needs to be converted from Meters to Feet
  - This process creates the input file (TB2, TB3, or TB3H file for US-supplied GDAS MET files) for the production code

Production Code Functions (1)

- Identify Vertical Track Level Segments
  - Group ADS-B flight data into two-minutes segments
  - Determine if the segment represents level flight
    - Binary classification model
  - Join all consecutive level flight segments into a final “inferred flight level” track, counting all tracks per flight
- Divide all flight tracks into five-minute sample periods
- Interpolate the MET data to HAE of the pressure measurement based on the aircraft location
  - This is done via function *f* that maps (Date, Time, Latitude, Longitude, and Pressure Altitude) to HAE
- Identify the number of ADS-B points available in each 5-minute period
  - 300 1-hz updates are expected, however, gaps can occur
- Calculate the mid-point of each segment (Lat, Lon) for ASE position analysis

Production Code Functions (2)

- Calculate the ASE at every point by subtracting the GPS altitude from the converted MET pressure HAE
  - Calculate the average and standard deviation of the ASE for each sample
- Calculate the Assigned Altitude Deviation (AAD) at every point by subtracting the reported pressure altitude from the track inferred flight level
  - Calculate the average and standard deviation for each sample
  - Assign the Small Height Deviation (SHD) index to each sample based on the average AAD
    - SMD 0 -> |ADD| between 0- 25ft
    - SMD 1 -> |AAD| between 25-50ft
    - SMD 2 -> |AAD| between 50-75ft
    - …
    - SMD 11->|AAD| between 275-300ft
  - SMD > 11 are Large Height Deviations (LHDs) and should be investigated
- Remove samples with N<60, NIC >7, or very high ASE Std Dev (>30ft)
- Create output data file for including in the database

Database Analysis and Sorting

- For all samples, database filters can be applied:
  - Standard Deviation less than 10 feet
  - ASE Samples must contain at least 250 of the expected 300 ADS-B points
- Only keep RVSM Flight Levels between FL290 and FL410 for ASE analysis
- Analyze data for Quality Control
  - Ensemble plots of ASE by time primarily for MET anomalies
  - Position plots of ASE, ASE Std Dev, AAD, and AAD Std Dev to identify possible geographic anomalies (Mountain Wave…)
- Analyze data for instances of stationary ground tests
- Approved ASE data is now available for aircraft analysis