PRELIMINARY FINDINGS OF *IN SITU* EDR RESEARCH

Michael Emanuel[1]
Federal Aviation Administration

Sal Catapano[2], Joseph Sherry[2], Jason Berger[2]
Exelis

Dr. Paul Robinson[3], Jason Prince[3]
AeroTech Research (ATR) U.S.A. INC

Larry Cornman[4], Dr. Gregory Meymaris[4] , Kent Goodrich[4]
National Center for Atmospheric Research (NCAR)

Dan Mulally[5]
Panasonic Avionics Corporation

Dr. Roger Dana[6]
Rockwell Collins

Rocky Stone[7]
United Airlines

Matthew Taylor[8]
WSI Corporation

1. INTRODUCTION

In response to industry recommendations, the Federal Aviation Administration (FAA) has initiated an Eddy Dissipation Rate (EDR) standards research project (herein referred to as the "project"), that includes recommendations for *in situ* EDR performance standards. This paper briefly describes the methodology and approach utilized by the project, documents preliminary findings, and describes continuing research activities. For greater detail, the project will be publishing its report in July 2014.

The term *in situ* EDR refers to the calculation of turbulence values by aircraft in-flight, where the turbulence metric, EDR, is intended to be an aircraft-independent, universal measure of turbulence based on the rate at which energy dissipates in the atmosphere.

The industry recommendations that prompted the FAA to initiate this research project were provided by the Automatic Dependent Surveillance-Broadcast (ADS-B) In Aviation Rulemaking Committee (ARC)[1] and RTCA Special Committee (SC) 206[2]. The ADS-B ARC and RTCA SC 206 recommended the FAA establish performance standards for *in situ* EDR values that are independent of computational approach.

In response to industry, the FAA assembled a team of subject matter experts from relevant domains to develop *in situ* EDR performance standard recommendations, as represented in Figure 1. The diverse and highly technical team includes *in situ* EDR algorithm developers, an avionics manufacturer, an airline, EDR data users, and experts in aircraft simulation capabilities.

In the field of *in situ* EDR algorithm developers, the team was represented by University Corporation for Atmospheric Research (UCAR), AeroTech Research (USA), Inc., (ATR), and Panasonic Avionics Corporation (formerly AirDat LLC) who have developed and/or implemented the algorithms being used by all existing operational implementations of *in situ* EDR. The project's avionics and aircraft systems expertise was provided by Rockwell Collins. In the user community, the team was represented by UCAR, the FAA's Graphical Turbulence Guidance (GTG) turbulence forecast developer; turbulence forecasters from WSI; as well as pilots from United Airlines. Aircraft simulation capabilities were a collaborative blending of the entire team.

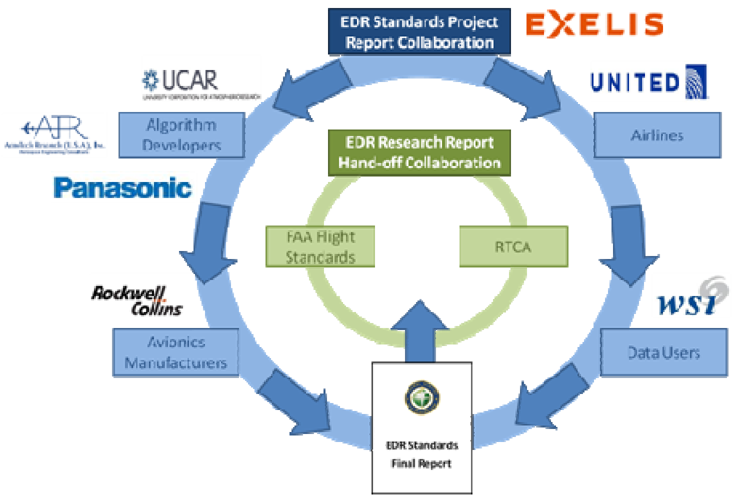


FIGURE 1: DIVERSE TEAM COMPOSITION

The team actively collaborated with both domestic and international stakeholders to develop a comprehensive community of interest that continues to provide valuable input into the development of the project's recommendations for *in situ* EDR performance standards. The EDR Standards Report will include recommended performance standards, as well as, a detailed description of the research, analyses, and findings supporting the recommendations. The report is intended to be used by standards and certification authorities, represented by the green inner circle of Figure 1, to ultimately define and adopt *in situ* EDR standards.

2. EDR STANDARDS PROCESS

The project has developed a process to support and justify its *in situ* EDR performance standard recommendations, as depicted in Figure 2. At its highest level, the process utilizes an assessment of current *in situ* EDR system performance, as well as current and anticipated user application objectives for EDR data to formulate recommended EDR performance standards.

The process is driven by the creation of wind datasets that are representative of real-world turbulence conditions and provide the ability to evaluate known performance limitations of *in situ* EDR. There are two categories of wind datasets developed, homogeneous and non-homogeneous. The homogeneous datasets represent continuous turbulence allowing for an evaluation of mean EDR performance, while the non-homogeneous allow for the evaluation of peak EDR.

The homogenous wind datasets enable the project to simulate the key characteristics of turbulence to include: the randomness of turbulence, varying turbulence length scales, and low severity levels that may be susceptible to aircraft and sensor induced noise. Since turbulence is a random process, datasets were created to replicate this fact to examine the EDR variability introduced solely by the random nature of turbulence. In addition, operational *in situ* EDR algorithms all assume a 500 meter turbulence length scale. However, in real-world conditions the length scale varies, therefore datasets were created with varying length scales (200, 750, 1000 meters). Aircraft sensors and avionics introduce noise to EDR calculations, therefore datasets at low turbulence severity levels (i.e., 0.01, 0.03 EDR) were generated to determine the corresponding impacts on EDR calculations during low signal-to-noise conditions.

For the non-homogeneous datasets, modulations were applied to simulate highly localized turbulence "bursts" representative of real-world turbulence events, such as mountain wave or convective turbulence. These modulations represent a range of severity levels through three modulation categories: Flat – a long low intensity burst, Mid – a sharper more intense burst, and Spike – a short very intense turbulence event.

Since the wind datasets are generated in a laboratory environment, the project was also able to derive EDR 'truth' for homogeneous turbulence and 'expected sample mean values' for non-homogeneous turbulence. These objective values were then used to compare against implementation resultant values to support the statistical analyses used in developing EDR performance standards.

In addition, the wind datasets are fed into an aircraft simulation to calculate algorithm input data that is representative of aircraft data used by operational EDR implementations (e.g., angle of attack, vertical acceleration, or true airspeed). These aircraft response parameters, used as inputs to calculate EDR, include sensor, avionics, and databus attributes such as quantization, thermal noise, filtering, etc. that are also simulated in the process.

The algorithm input data provide simulated *in situ* EDR algorithm inputs for the three EDR calculation methodologies. Each *in situ* EDR implementer (i.e., ATR, Panasonic, and UCAR) applied their respective operational algorithm to perform pseudo-operational runs producing datasets of 1-minute mean and peak EDR values.

A statistical analysis was then performed, comparing resultant values from the pseudo operational runs against EDR 'truth' or 'expected sample mean values'. The results from the statistical analysis provide a characterization of today's *in situ* EDR operational performance. A quantitative, statistical analysis enables a uniform approach for determining today's *in situ* EDR performance. Today's operational performance combined with user community performance objectives are the basis, for performance standards recommendations.

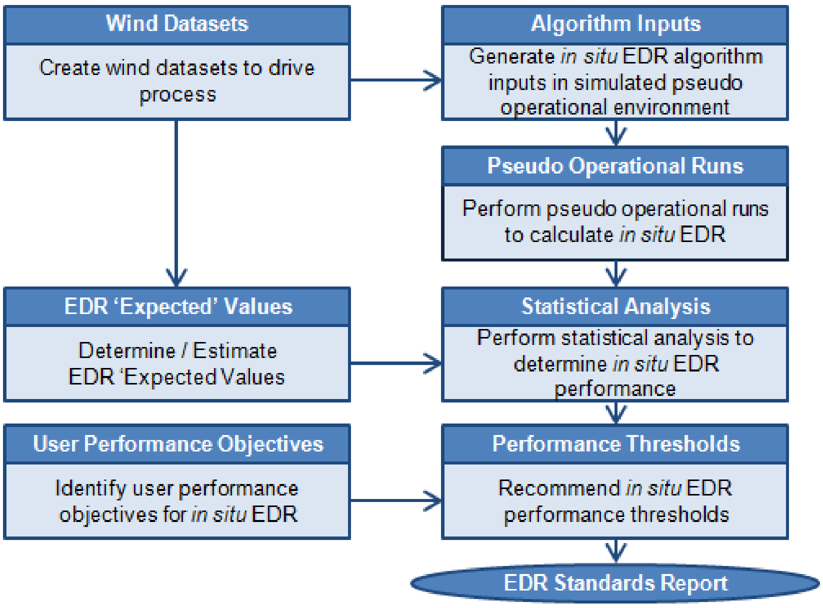
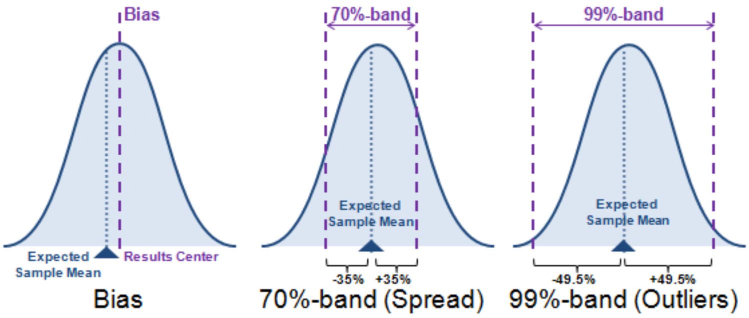


FIGURE 2: EDR STANDARDS PROCESS FLOW CHART

3.0 Statistical Analysis Approach

Statistical analyses were performed for each of the cases studied to determine performance of current *in situ* EDR implementations across a range of conditions. In generating its performance standard recommendation, the project selected three statistics to characterize the performance of today's implementations (Bias, 70%-band, and 99%-band). Bias characterizes how centered the implementations' results are relative to a reference value (e.g., EDR 'truth'). The 70%-band characterizes the spread or tightness of the results and the 99%-band bounds the results such that only the most severe outliers are excluded. Figure 3 graphically depicts these statistics.



Note: All example figures indicate a positive bias (i.e., bell curve shifted right of EDR_{Truth} center)

FIGURE 3: STATISTICS USED TO DETERMINE PERFORMANCE

Bias is calculated as the difference between a reference value (i.e., expected sample mean) and the square root of the mean, of the squares of the values in the sample.

The tolerance bands that the project employed quantify the percentage of data within a specified range about a reference value. For the homogeneous turbulence case (mean EDR statistics), the team used the 'truth' as this reference value. And, for the non-homogeneous turbulence case (peak EDR statistics), the team is considering calculating the tolerance bands using either the expected sample mean value or the sample mean as the reference value. Figure 4 illustrates the differences between these two methods. The expected sample mean is the red dot at the center of the target. The red tolerance bands quantify the range relative to the expected sample mean that contains a specified percentage of the distribution. The sample mean, the blue dot, of a distribution is usually offset some distance from the expected sample mean (i.e., it has some bias). The blue tolerance bands quantify the range relative to the sample mean that contains a specified percentage of the distribution. When bias is zero these two approaches produce the same results.

All these statistics are normalized and expressed as percentages of the 'truth' or 'expected sample mean' reference value allowing for easy comparison across varying levels of turbulence intensity, window length, etc.

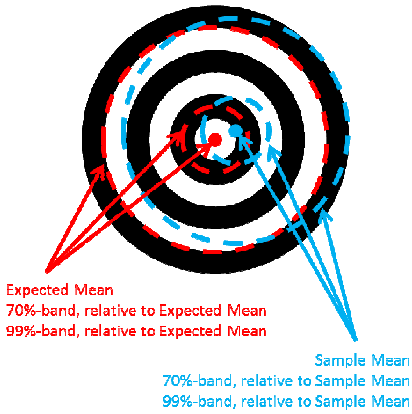


FIGURE 4: EXPECTED VS. SAMPLE MEAN VALUE

4.0 PRELIMINARY MEAN EDR STATISTICAL ANALYSIS RESULTS

The statistical analysis results from the homogeneous wind datasets are depicted in Figure 5, where the x-axis is the EDR_{Truth} severity level from 0.01 to 0.7, and the y-axis is the performance as a percentage of the respective EDR_{Truth} value. Figure 5 provides the project's statistical results (i.e., bias, 70%-band, and 99%-band) for all implementations. Note that all operational algorithms have statistical performance equal to or better than these statistical percentages of the respective EDR_{Truth} values.

At 0.01 EDR, the project found 1-minute mean EDR reports incorporate a high-level of bias due to aircraft sensor/avionics noise, which is airframe/avionics dependent (i.e., not always limited to 0.01 EDR). Above 0.01 EDR, this noise-based bias quickly diminishes, as the signal-to-noise ratio increases.

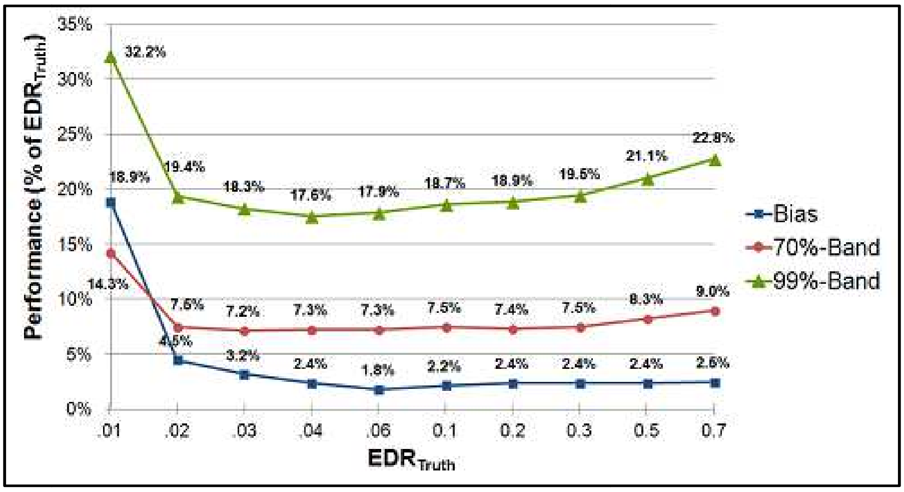
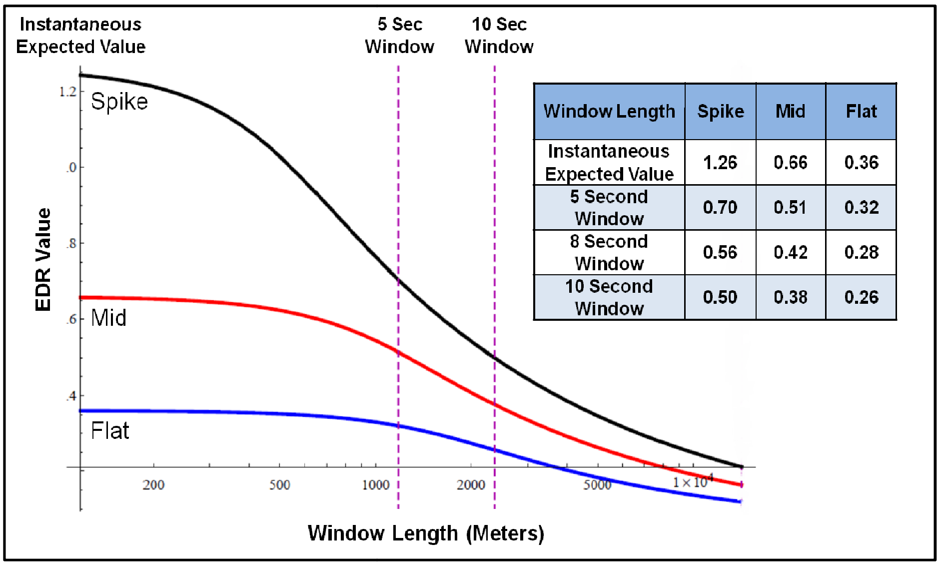


FIGURE 5: PRELIMINARY MEAN EDR STATISTICAL ANALYSIS RESULTS

5.0 PRELIMINARY PEAK EDR STATISTICAL ANALYSIS RESULTS

Also of interest is *in situ* EDR performance in very sudden and intense turbulence (e.g., convective, mountain wave induced). To study this, wind fields of short duration and greater intensity turbulence bursts were generated and classified as: Flat, Mid, and Spike.

Figure 6 illustrates the spectral scaling method developed and utilized by the project to calculate ‘expected sample mean values’, which are a function of window length, for each modulation dataset. The x-axis represents window length (meters), which is converted to window length (seconds), using an aircraft speed of 236 m/s and the y–axis is the EDR value. The blue, red, black curves represent the ‘expected sample mean values’ of the project generated datasets using the ‘spectral shifting’ method. To calculate EDR, algorithms must have a significant sample of data to process (i.e., window length). An instantaneous EDR value is represented as the limit as the window length goes to zero.



Window Length	Spike	Mid	Flat
Instantaneous Expected Value	1.26	0.66	0.36
5 Second Window	0.70	0.51	0.32
8 Second Window	0.56	0.42	0.28
10 Second Window	0.50	0.38	0.26

FIGURE 6: PEAK EDR INSTANTANEOUS VALUES VS. EXPECTED SAMPLE MEAN VALUES

The window lengths employed by current operational *in situ* EDR algorithms vary from 5-10 seconds. For window length selection there are at least two factors to consider: 1) the standard deviation of the peak EDRs calculated from a dataset will typically increase with decreasing window length and 2) the bias (i.e., the difference between the instantaneous expected value and that of a specific window length) will increase with increasing window length. From Figure 6 one can see that the ‘expected sample mean value’, using the same wind input dataset, decreases with increasing window length. For example, the Spike dataset has an expected sample mean value of 1.26 EDR for an instantaneous window length, whereas 5, 8, and 10 second window lengths are 0.70, 0.56, and 0.50, respectively.

All implementations performed as expected, in that their statistical average over a large sample of 1-minute peak EDR reports conforms to their respective ‘expected’ sample mean values. However, it was found that across each 1-minute report there was significant inconsistency among implementations. The reason for this is *in situ* EDR implementations employ different window lengths, parameter settings, and methodologies, some of which can result in inconsistent peak EDR calculations in very sudden intense turbulence (i.e., non-homogeneous). The result of the inconsistencies due to the different window lengths (and other parameters) is that EDR data from one window length cannot meaningfully be compared to data from another. This would lead to uncertainty in interpreting the EDR data from different aircraft implementations. Therefore, the project elected to pursue continuing research through the performance of sensitivity analyses in an effort to quantify the sources of these inconsistencies.

6.0 SENSITIVITY ANALYSIS

For future tactical uses of EDR, such as crosslinking *in situ* EDR reports between aircraft, high levels of peak EDR report consistency across implementations may be required. The goal of the sensitivity analyses is to leverage findings, along with common target-criteria (where available), to allow the *in situ* EDR implementers to experiment with their respective algorithms to identify changes that might help improve consistency in peak EDR reports across implementations and define a more standard implementation approach to use as a reference or baseline in defining peak EDR performance standards.

It is important to note that the parameters and calculation methodologies included in the sensitivity analysis should not be considered the only algorithm elements that may lead to inconsistency; rather it includes those the team thought should be looked at first.

It must be stressed that the project is not directing implementers to make any changes to their operational algorithms. Rather, it creates an opportunity for the implementers to study their choices and make changes as they feel appropriate.

7.0 PRELIMINARY FINDINGS

Today’s Mean EDR Performance

For 1-minute mean *in situ* EDR reports, the project took advantage of the fact it could provide ‘truth’ values for homogeneous turbulence. By comparing these ‘truth’ values with results from pseudo-operational runs the project concluded all current implementations provide mean EDR reports over a statistically significant sample, with a high-level of consistency across implementations, as well as, turbulence severity levels and length scales.

Key Takeaway: All of today's implementations consistently and accurately calculate 1-minute mean in situ EDR reports above the noise floor created by aircraft sensors and avionics (on or about 0.01 to 0.02 EDR).

For very low turbulence intensities, aircraft sensor and avionics noise causes a significant increase in bias of mean EDR reports. The noise floor for the project's simulation was determined, based on real-world flight data, to be between 0.01 EDR and 0.02 EDR. However, it is important to know that the noise floor is sensor and avionics dependent, and may vary somewhat from the noise floor determined in the project's simulation. Below that noise floor, 1-minute mean *in situ* EDR report error was found to be very high because of the contribution of noise. Above the noise floor bias and band statistics quickly improve (as the signal-to-noise ratio increases).

Key Takeaway: For 1-minute mean in situ EDR reports at very low turbulence severity levels (e.g., 0.02 EDR or below), aircraft sensor and avionics will impact the accuracy of the reported EDR.

Today's Peak EDR Performance

A challenge for the project was the inability to discover or determine 'truth' values for 1-minute peak *in situ* EDR reports. However, the project was able to determine the 'expected sample mean values' for the datasets the project generated, which proved very useful in determining bias statistics.

All existing *in situ* EDR implementations employ different window lengths (i.e. sample sizes), parameter settings (e.g., window function and overlap, and frequency cutoffs), algorithm inputs (i.e., vertical winds, TAS, vertical acceleration), and methodologies (e.g., spectral, temporal). While some of these differences do not contribute greatly to inconsistency of 1-minute peak *in situ* EDR reports across implementations (e.g., the choice of vertical acceleration as algorithm input over vertical winds), some (e.g., window length and function) do result in significant inconsistency.

Key Takeaway: Current 1-minute peak in situ EDR reports across implementations can be inconsistent given different algorithm implementation approaches.

It could also be argued that a very significant factor influencing inconsistencies in peak EDR reports, in an operationally setting, is the random nature of turbulence itself. Even for very small changes in time and space, all other factors remaining equal (e.g., same EDR algorithm, same aircraft type), there can be significant differences in EDR reports.

Key Takeaway: No matter how accurate or consistent we make in situ EDR implementations, their performance is limited by atmosphere conditions we cannot control.

8. SUMMARY

The preliminary findings of the project found that all existing *in situ* EDR implementations calculate mean EDR accurately and consistently for homogeneous turbulence. However, all existing *in situ* EDR implementations employ different data sampling window lengths, parameter settings, and methodologies, yielding inconsistent peak EDR values in very sudden intense turbulence.

In an effort to reduce these inconsistencies between implementations the project is performing a sensitivity analysis as continuing research with the goal of reducing inconsistencies across algorithms. The findings of the sensitivity analysis, along with a more in depth narrative of the project's discovery, process, findings, and performance recommendations can be found in the project's FAA EDR Standards Report, scheduled for delivery to the FAA in July, 2014.

---

[1]*Author address:* Michael Emanuel, Federal Aviation Administration, William J. Hughes Technical Center, Atlantic City International Airport, NJ, 08405;

[2]Author address: Sal Catapano, Exelis, 600 Maryland Ave, Suite 700E, Washington DC, 20024;

[2]Author address: Joseph Sherry, Exelis, 600 Maryland Ave, Suite 700E, Washington DC, 20024;

[2]Author address: Jason Berger, Exelis Inc. 12930 Worldgate Drive, Herndon, Virginia 20170

[2]Author address: James Stafford, Exelis Inc. 12930 Worldgate Drive, Herndon, Virginia 20170

[3]Author address: Dr. Paul Robinson, AeroTech Research (ATR) U.S.A. Inc., 11836 Fishing Point Drive, Suite 200, Newport News, VA, 23606;

[3]Author address: Jason Prince, AeroTech Research (ATR) U.S.A. Inc., 11836 Fishing Point Drive, Suite 200, Newport News, VA, 23606;

[4]Author address: Larry Cornman, National Center for Atmospheric Research (NCAR), 3450 Mitchell Lane, Boulder, CO, 80301;

[4]Author address: Dr. Gregory Meymaris, National Center for Atmospheric Research (NCAR), 3450 Mitchell Lane, Boulder, CO, 80301;

[4]Author address: Kent Goodrich National Center for Atmospheric Research (NCAR) 3450 Mitchell Lane Boulder, Colorado 80301

[5]Author address: Daniel Mulally, Panasonic Avionics Corporation, 10901 W Toller Drive, Suite 300 Littleton, Colorado 80127

[6]Author address: Dr. Roger A. Dana, Rockwell Collins, 400 Collins Road NE, Cedar Rapids, Iowa 52498; radana@rockwellcollins.com

[7]Author address: Rocky Stone, United Airlines
233 South Wacker Drive, 2371-H, WHQZT
Chicago, Illinois 60606

[8]Author address: Matthew Taylor, WSI Corporation, 2201 Cooperative Way, Herndon, VA 20171;

9. REFERENCES

[1]Recommendations to Define a Strategy for Incorporating ADSB-In Technologies into the National Airspace System. A Report from the ADS-B Aviation Rule Making Committee to the Federal Aviation Administration. September 30, 2011.

[2]Aircraft Derived Meteorological Data via ADS-B Data Link for Wake Vortex, Air Traffic Management, and Weather Applications. Operational Services and Environmental Definition. RTCA 206 Sub-Group 1.

Note the FAA EDR Standards Project has developed a publically available spreadsheet that includes reference data for all of the literature located during the project's EDR literature search. The reference data included in the spreadsheet is intended to allow an individual to perform a basic internet search and locate the literature desired. The spreadsheet can be obtained by contacting Sal Catapano at salvatore.catapano@exelisinc.com