Parametric Uncertainty Quantification of AEDT

Project 36

Project manager: Mohammed Majeed, FAA
Lead investigator: Dimitri Mavris (PI) and Yongchang Li (Co-PI)
Georgia Institute of Technology

Presenter: Dr. Yongchang Li, Georgia Institute of Technology

April 18th & 19th, 2019
Atlanta, GA

ASCENT
AVIATION SUSTAINABILITY CENTER

Introduction

- Aviation Environmental Design Tool (AEDT) is the heart of the FAA's environmental tool suites for assessing fleet wide fuel burn, emissions, and noise impacts
- As AEDT sets the global standard for environmental impact analysis, it is under continuous improvements to implement the best modeling methods and data
- FAA is interested in quantifying uncertainties in AEDT output due to uncertainties in input parameters
- The main objectives of this research are to
  1. Perform Verification and Validation (V&V) for new methods and functionalities implemented to AEDT sprint releases
  2. Identify and quantify major contributors to output uncertainties
  3. Identify gaps in the tools functionality and areas for further development

Practical Outcomes

- Short term
  - Perform capability demonstrations
  - Perform V&V for new methods and functionalities implemented to AEDT sprint releases
  - Perform system level parametric uncertainty/sensitivity analysis
- Long term
  - Contribute to the external understanding of AEDT
  - Help users of AEDT to understand sensitivities of output response to variation in input parameters/assumptions
  - Identify gaps in functionality
  - Identify high-priority areas for further research and development
  - Build confidence in AEDT's capability and fidelity (ability to represent reality)

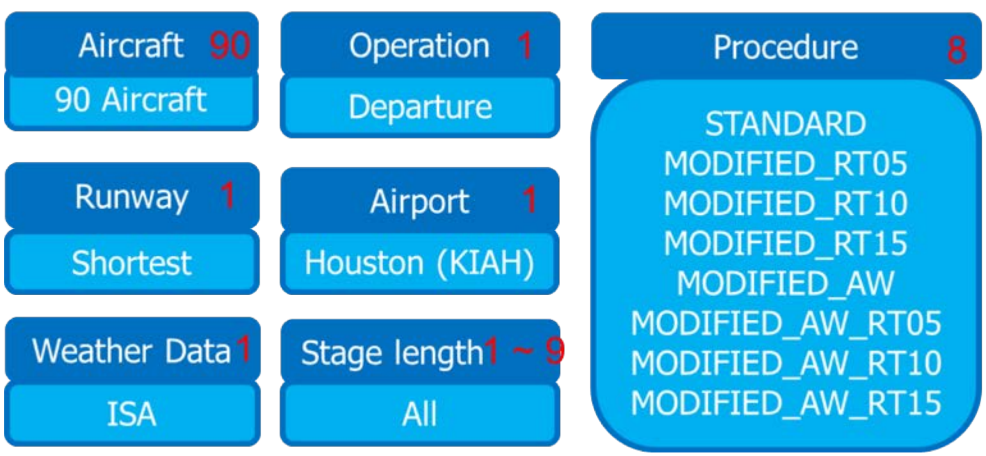
Research Approach

- AEDT development team has been exercising the agile development process
- For each AEDT sprint, depending on the type of updates,
  - identify the key features and functionalities to conduct capability demonstration
  - identify the best available methods and data to conduct V&V
  - identify the key sources of uncertainties and the best approach to conduct parametric uncertainty analysis
- The main features/capabilities that were added to AEDT

BADA4	Emissions	Noise	Others
Implementation of procedural departures and arrivals	Emission concentration display for non-closing contours	Dynamic grid for non-dB metrics	ANP Reduced thrust and alternative weight depature procedures
BADA4 reduced thrust and alternative weight depature procedures	Emissions dispersion modeling	Noise cutoff altitude	Track control
Climb thrust taper	Enhanced nvPM methods	Detailed noise results report	FLEET Update
Data Encryption			

UQ on Reduced Thrust (RT) and Alternative Weight (AW) Departure Procedures

- Reduced Thrust (RT) and Alternative Weight (AW) departure procedures are implemented in AEDT 3a
- AEDT study consisting of 7124 cases were created to thoroughly test these procedures were implemented correctly
- Fuel burn, emissions and noise results of the new procedures for all the stage lengths of each aircraft were compared

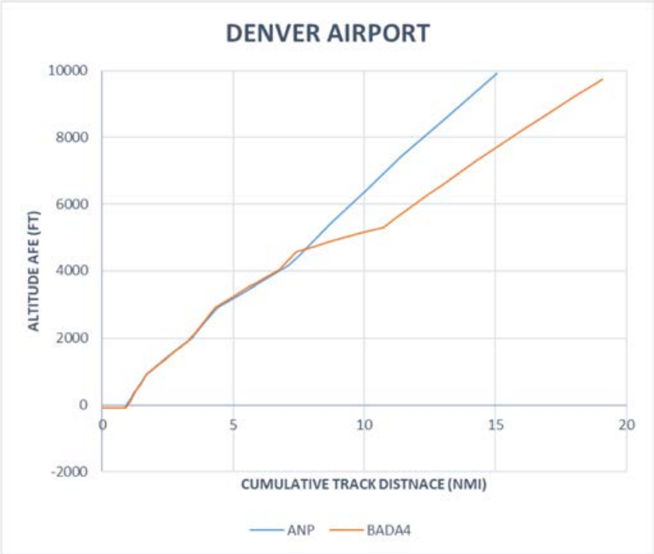


717200			
Profile	SL 1	Fuel Burn	Difference %
STANDARD		612.21	0
MODIFIED_RT05		612.71	0.08
MODIFIED_RT10		625.23	2.13
MODIFIED_RT15		625.82	2.22
MODIFIED_AW		622.71	1.72
MODIFIED_AW_RT05		623.14	1.79
MODIFIED_AW_RT10		636.53	3.97
MODIFIED_AW_RT15		637.18	4.08

- All cases ran successfully
- Fuel Burn, NOx, and noise result comparisons to STANDARD profile were calculated for each stage length of all 90 aircraft, and the comparisons show proper trends

UQ on BADA4 Implementation with RT/AW Procedures

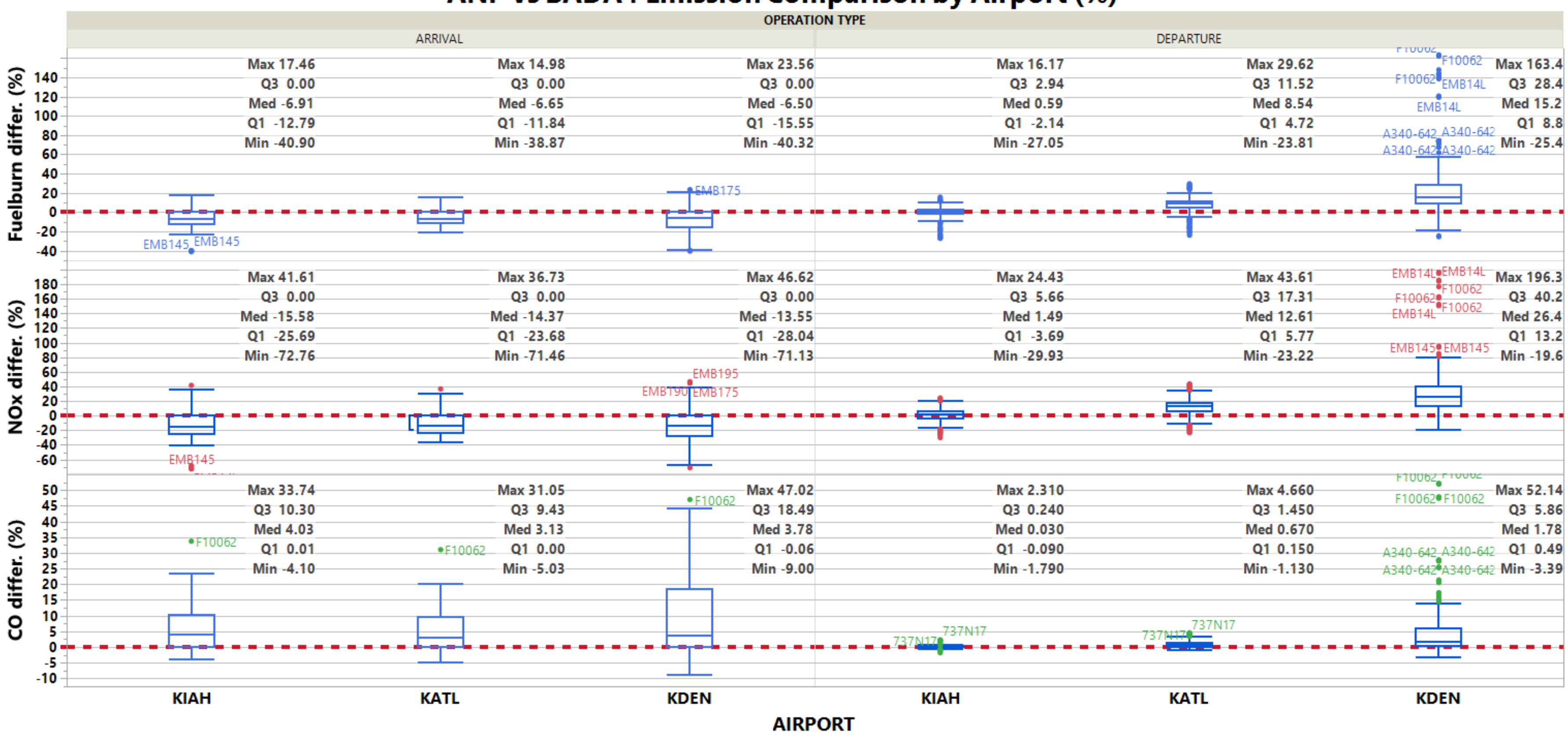
- Procedure-based flight performance model using BADA4 has been implemented in AEDT
- A study with 4428 cases was performed to assess the implications of BADA4 in AEDT, and compare ANP and BADA4 models
  - 41 aircraft with BADA4 model
  - 2 operations (departure, arrival)
  - 3 airports (KIAH, KATL, KDEN)
  - 2 weather profiles (normal and hot day)
  - 8 profiles (1 STANDARD + 7 RT/AW profiles)



UQ on BADA4 Implementation with RT/AW Procedures

- Fuel Burn and Emissions Results
  - BADA4 departure fuel burn is greater by 12.6% on average due to the implementation of the 250 knot limit using 10,000 ft MSL, resulting in a longer distance flown
  - BADA4 arrival fuel burn is 7.6% less on average which results from difference in arrival modeling
  - BADA4 NOx is greater for departure and less for arrival than ANP

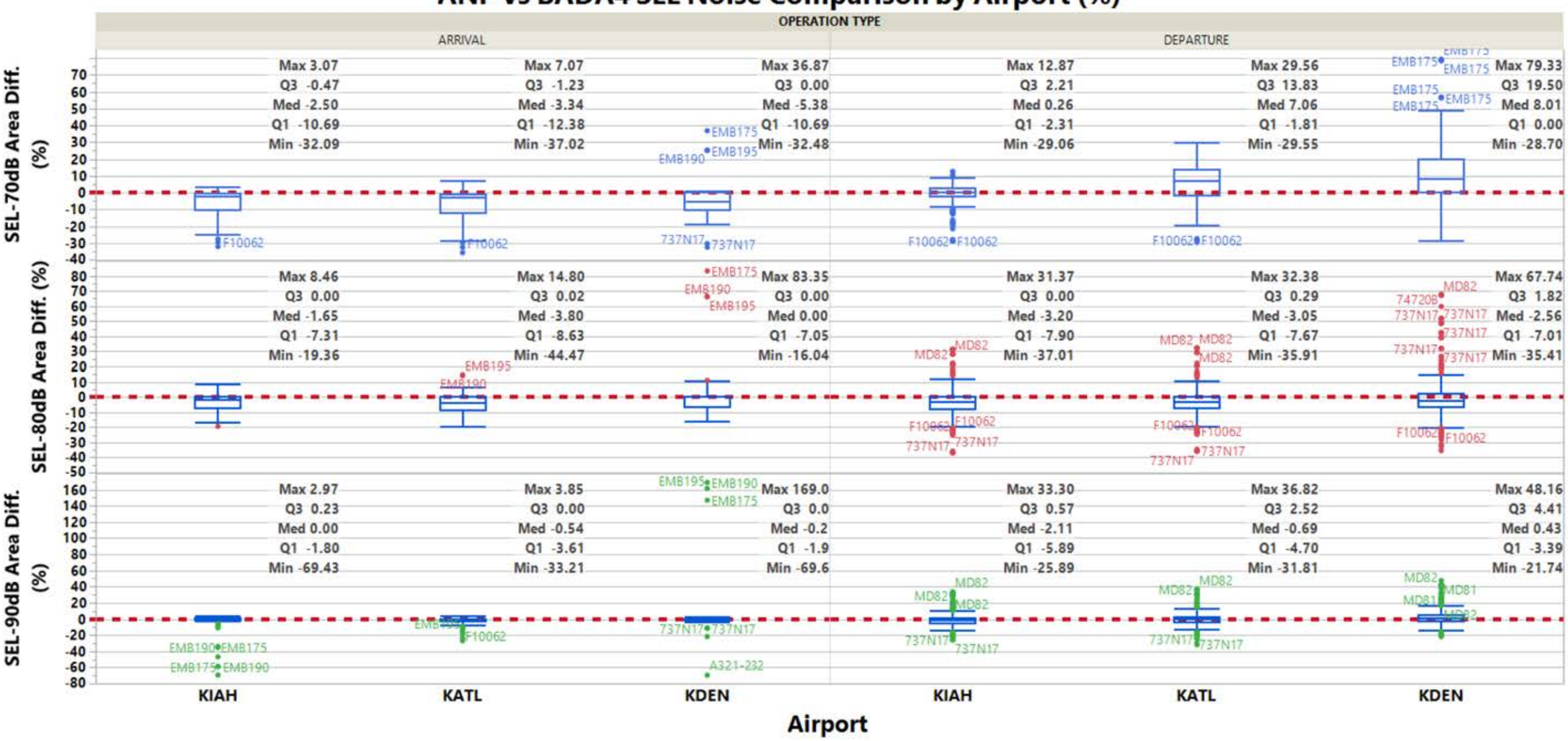
ANP vs BADA4 Emission Comparison by Airport (%)



UQ on BADA4 Implementation with RT/AW Procedures

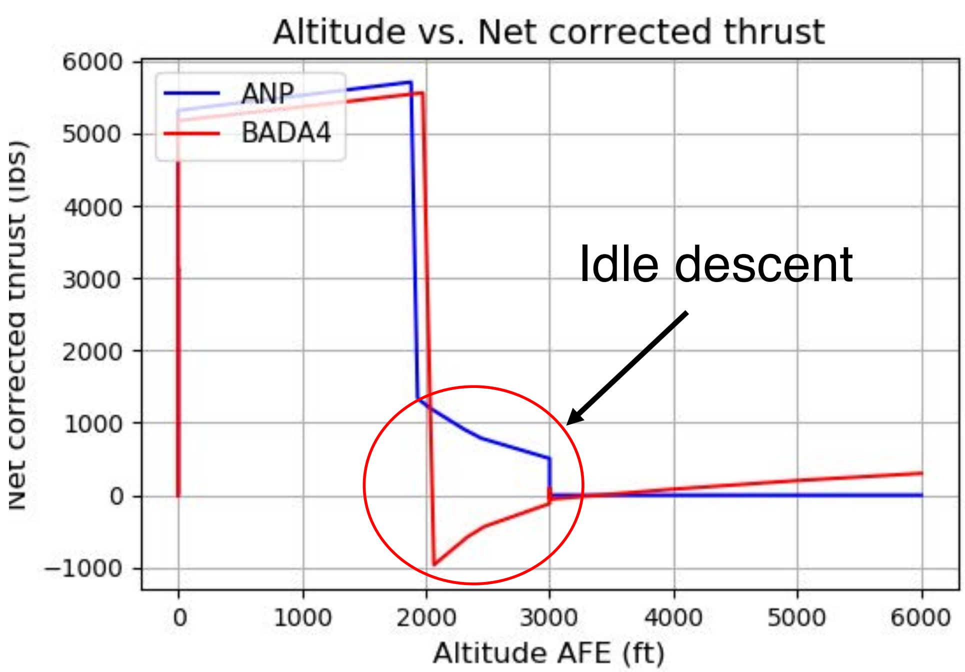
- Noise Results
  - For majority of the aircraft studies, the difference in noise results are relatively small, especially for high level dB
  - Bigger noise differences are observed at high altitude airport and on hot day, especially for low level dB
  - This is due to BADA4 has shallower trajectory at high altitude airport

ANP vs BADA4 SEL Noise Comparison by Airport (%)



Idle Descent V&V for ANP and BADA4

- For arrival operation, ANP and BADA4 differ mostly in idle descent segment due to different equations/coefficients used in thrust calculations
- Through extensive studies, the impact of idle descent segment was found to be relatively small for overall emission and noise results
- BADA4 model always take deceleration into account in the descent segment while ANP does not, thus BADA4 generates more accurate results



ANP:

$$\frac{F_n}{\delta} = E + Fv + G_A h + G_B h^2 + HT_c$$

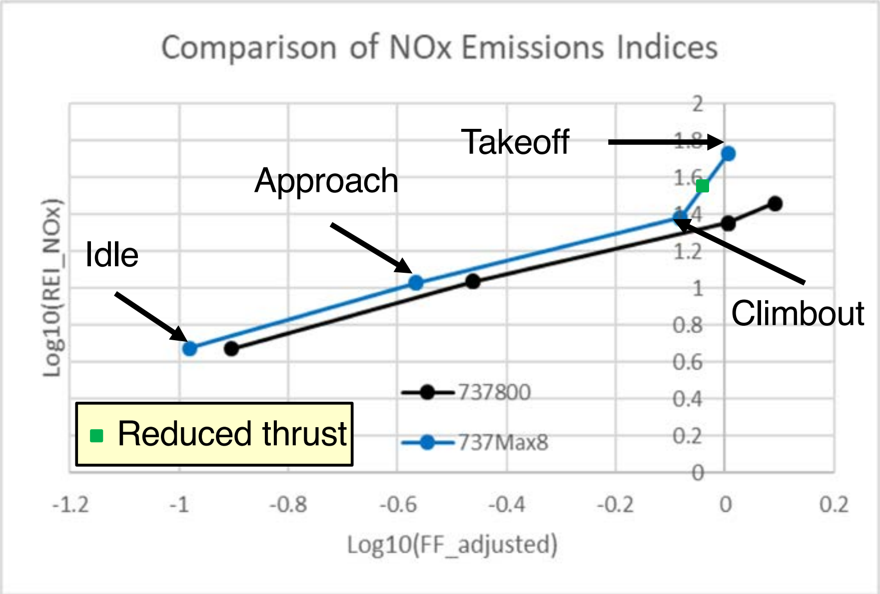
BADA4:

$$Th = \delta W_{mref} C_T$$

$$C_T = ti_1\delta^{-1} + ti_2 + ti_3\delta + ti_4\delta^2 + (ti_5\delta^{-1} + ti_6 + ti_7\delta + ti_8\delta^2) \cdot M + (ti_9\delta^{-1} + ti_{10} + ti_{11}\delta + ti_{12}\delta^2) \cdot M^2$$

NOx Calculation V&V

- It was discovered that NOx differences were relatively larger than fuel burn in reduced thrust comparison for some aircraft, e.g. 737MAX8
- An EXCEL based tool was developed using Boeing Fuel Flow Method 2 (BFFM2) to verify AEDT NOx calculation
- Analysis revealed that 737MAX8 has a bigger slope in the log-log curve used to calculate NOx, thus small thrust reduction can result in big NOx difference
- BFFM2 method in AEDT was verified, and the AEDT technical manual was updated for clarification



$$NO_xEI = NO_xREIe^H\left[\frac{\delta^{1.02}}{\theta^{3.3}}\right]^{0.5}$$

$$H = -19\left[\frac{0.62197058\phi P_v}{P - \phi P_v} - (6.34 * 10^{-3})\right]$$

Where:

NO_xEI at non-reference conditions (g/kg)

NO_xREI at reference conditions (g/kg)

δ is the static pressure ratio

θ is the static temperature ratio

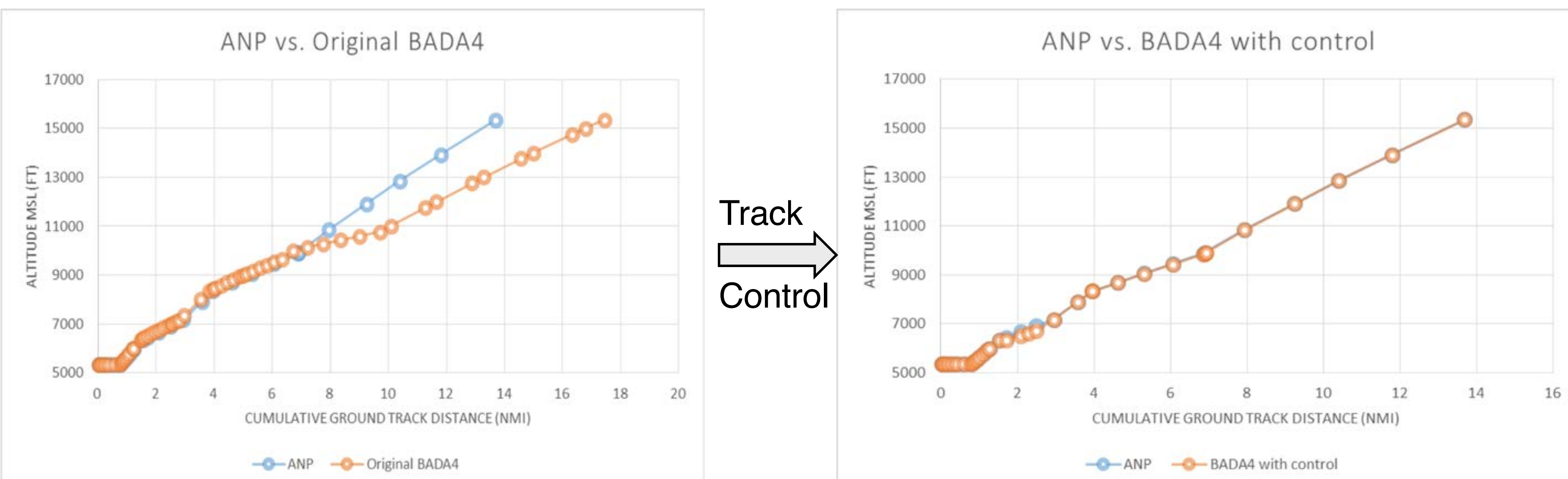
P is the ambient pressure (psi)

P_v is the saturation vapor pressure (psi)

ϕ is the relative humidity

UQ on Track Control

- A track control flight defines what aircraft’s altitude/speed must be as it passes over a particular track point
- UQ on track control
  - Demonstrated the track control functions with ANP and BADA4
  - Conducted thorough tests on the track control input requirements
  - To resolve the difference in trajectory between ANP and BADA4 for high elevation airport, created track with controls for BADA4 using ANP trajectory
- Track control features were fully functional and worked properly



Parametric Uncertainty Quantification for BADA4

- **Target**: perform a system-level parametric uncertainty analysis on BADA4, and identify the main contributors to AEDT output uncertainties

Step 1 — **Uncertainty Characterization**
- **Identify** inputs and outputs parameters
- **Mapping** of key BADA4 inputs to key environmental metrics based on literature review and expert knowledge
- **Specify the variability** of input parameters
- **Correlation analysis** of input parameters (when data is available)

Step 2 — **Sensitivity Analysis**
- **One-factor-at-a-time (OFAT) design of experiments**: change each input parameter one at a time while fixing other parameters at baseline values

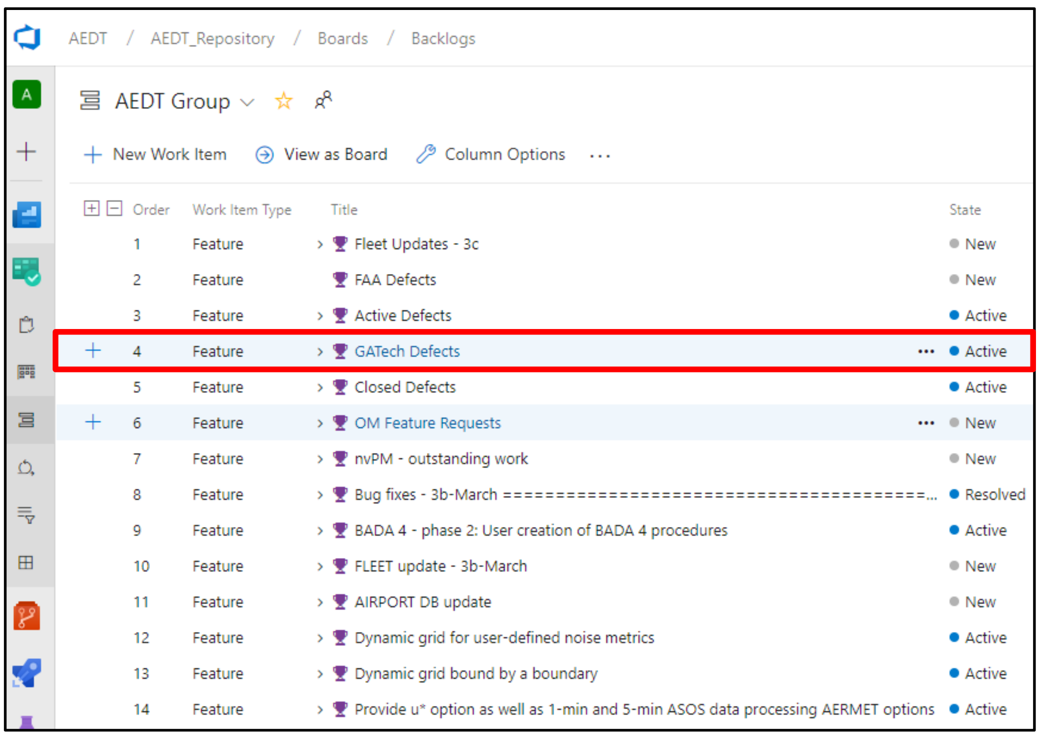
Step 3 — **Uncertainty Propagation**
- **Screening Test**: to reduce the number of variables for surrogate models
- **Surrogate Modeling**: Artificial Neural Network (ANN)
- **Monte Carlo Simulation**
- **Copulas theory** is used to capture correlation between input parameters

Step 4 — **Global Sensitivity Analysis**
- Assess the impact of the input parameters on the outputs
- **Total sensitivity index (TSI)** can measure the relative impact of each of the input parameters

- Identified total 263 factors including ANP, BADA4 and weather coefficients, and specified the variability for input parameters
- Sensitivity analysis is ongoing

Interfaces and Communications

- External
  - Bi-weekly telecon with the FAA management
  - Weekly telecons with the AEDT development team
  - On-line communication via Team Foundation Server (TFS)



- Within ASCENT
  - P45, P43, P10
  - FAA, Volpe, ATAC, Metron
- Report
  - Quarterly report
  - Annual Report

Summary/Next Steps

- GT team is working very closely with the AEDT development team to conduct independent V&V of the current and future AEDT versions
- GT has tested and verified that the AEDT's new capabilities are working properly
- GT has identified some bugs and needs for minor improvements → **Most of them have already been addressed by the development team!**
- GT will perform sensitivity analysis and uncertainty quantification as necessary
- Document the findings on TFS for the developers and AEDT UQ reports for the general public
- GT will remain flexible and use the best available methods and data in order to ensure accuracy and functionalities of future AEDT versions
- Primary next steps:
  - Continue the parametric UQ on BADA4
  - User defined BADA4 procedure
  - NO2 emission dispersion modeling
  - Supersonic LTO noise
  - Perform independent testing and uncertainty analysis for any newly released features and functionality

References

- US FAA, AEDT 2b UQ Report, 2016
- US FAA, AEDT 2d Technical Manual, 2018
- [US FAA, AEDT 2d User Manual, 2018
- Noel, George, "AEDT Uncertainty Quantification", presented in FAA/AEE Tools Review, December 2010
- Willcox, "Tools Uncertainty Quantification", presented in FAA/AEE Tools Colloquium, December 2010
- Allaire and Willcox, "Surrogate Modeling for Uncertainty Assessment with Application to Aviation Environmental System Models", AIAA Journal, 2010
- EUROCONTROL, Base of Aircraft Data (BADA) Aircraft Performance Modeling Report, EEC Technical/Scientific Report No. 2009-009, March 2009

Publications

- Yongchang Li, Dongwook Lim, Michelle Kirby, Dimitri Mavris, George Noel, Uncertainty Quantification Analysis of the Aviation Environmental Design Tool in Emission Inventory and Air Quality Modeling, AVIATION 2018 conference, June 17 – 21, 2018.
- Dongwook Lim, Yongchang Li, Matthew J Levine, Michelle R Kirby, Dimitri, Mavris, Parametric Uncertainty Quantification of Aviation Environmental Design Tool, AVIATION 2018 conference, June 17 – 21, 2018.
- Jung-Hyun Kim, Kisun Song and Seulki Kim, Yongchang Li, Dimitri Mavris, Aircraft Mission Analysis Enhancement by using Data Science and Machine Learning Techniques, Submitted to AVIATION 2019 conference

Contributors

Georgia Tech Team:

Prof. Dimitri Mavris (PI), Dr. Yongchang Li (Co-PI), Dr. Dongwook Lim (co-PI), Dr. Michelle R. Kirby

Graduate Students:

Zhenyu Gao, Junghyun (Andy) Kim, Yee Chan (Daniel) Jin, Ameya Behere

FAA-AEE: Dr. Mohammed Majeed (PM), Joseph DiPardo, Bill He

AEDT Development Team: George Noel (Volpe)