Definition and Demonstration of a Methodology for Validating Aircraft Trajectory Predictors

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Outline

- Motivation
- TP Validation Overview
- TP Validation Methodology
  - Core Techniques
  - Procedural Framework
- Case Study: Application to ERAM validation
  - FAA Validation Results
  - Example benefits of applying new techniques
- Concluding Remarks

Motivation

- Prediction of 4D aircraft trajectories is cornerstone of future international ATC/ATM concepts
  - U.S. NextGen: Trajectory Based Operations
  - European SESAR: Business Trajectory
- Decision Support Tools (DSTs) using an aircraft trajectory predictor (TP) provide these trajectories

  => DST Validation required. Why independent TP validation?
- Past: Independent TP Validation not performed
  - TP indirectly validated by validating TP-dependent DST functionality
- Benefits of independent TP validation methodology
  - Supports development of Common TP capabilities
  - Improves DST validation by validating major component

TP Validation Overview

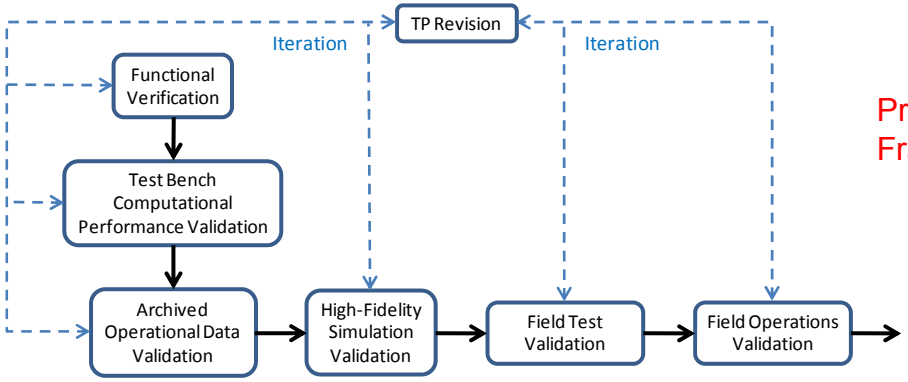
- Focuses on two exercises
  - Functional Verification
    - Confirms TP performs required functions under required conditions (*functional requirements*)
  - Performance Validation
    - Confirms TP performance is within acceptable limits (*performance requirements*)
    - Primary performance requirements:
      - Computational speed
      - Prediction accuracy (most challenging)

- Two classes of TP requirements
  - Direct requirements
    - Define explicit requirements for TP functionality or performance
    - Example: Maximum predicted altitude error or response time
  - Indirect requirements
    - Define required overall system performance for TP-dependent functions
    - Example: Conflict probe false alarm/missed alert rate
  - Not uncommon to have a mixture of both classes
    - Very common today to have more indirect requirements
  - Validation for the different classes requires different approaches

TP Validation Methodology

- Goal: Avoid costs from failures during single-stage, pass/fail validation
- Recognizes:
  - Iteration likely required to achieve validation success
  - Collection of validation data (simulation, field test, operational) can be expensive
    - Iteration can incur costs multiple times
- Core techniques
  - Main approaches used within and to define various stages of validation process
- Procedural framework
  - Overall process as applied to validation of TP
  - Not required steps, but validation options and guidance to create a complete validation effort

Core Techniques
- Use validation stages
- White box testing
- Test bench testing



Procedural Framework

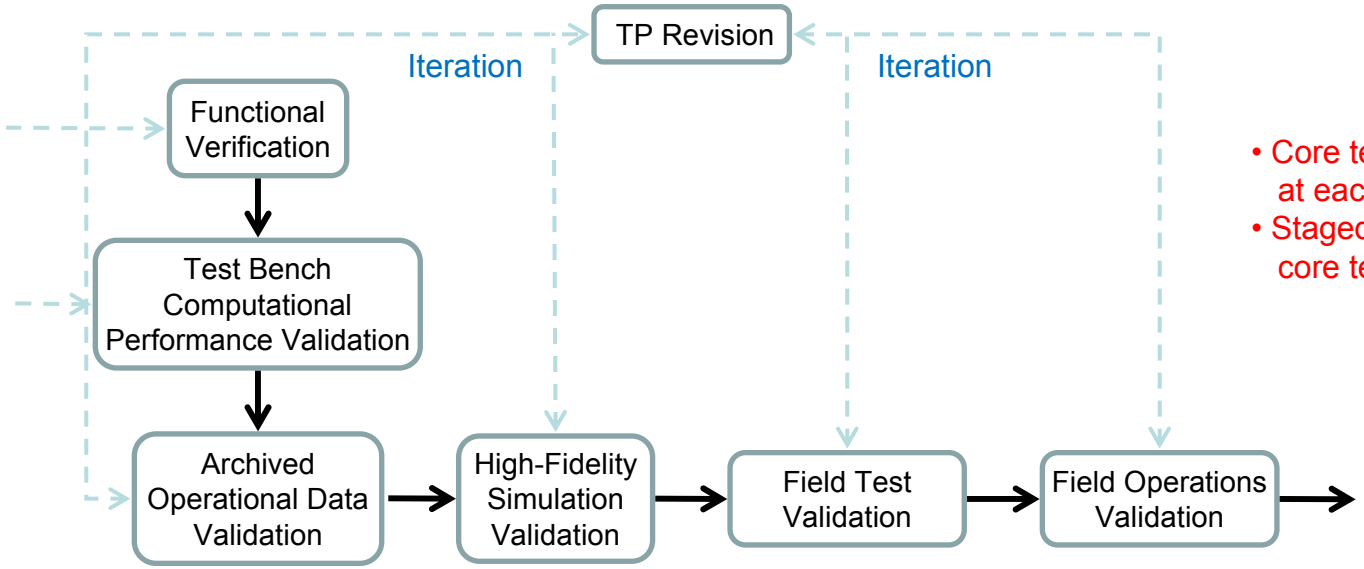
TP Validation Methodology:
Core Techniques

- Use of validation stages
  - Perform validation as a series of (potentially iterative) validation efforts
    - Minimize costs if one or more requirements not met
    - Reduces overall effort in meeting all requirements
  - Applications:
    - Framework: Start with simpler, cheaper efforts that are necessary, but not sufficient
      - Iterate at earlier stages before most significant costs incurred
    - Validate requirements in sequence, not all at once
      - Start with requirements whose success improves chances of achieving other requirements
      - Example: direct requirements before indirect requirements

- White box testing:
  - Use knowledge of internal TP processing to isolate error sources during testing
    - Identify potential critical error sources when performing validation tests
    - If test fails, test results support identification of impact of the various error sources
      - Improves identification of required TP modifications during iteration
  - May only require collecting some additional data during planned tests
    - Identifiable from input data
    - No extra test cases added
  - Example: identifying which cases have or don't have lateral routing errors

TP Validation Methodology:
Procedural Framework

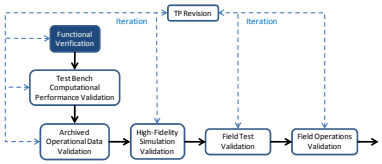
- Provides a series of validation stages
  - Increasing fidelity and, typically, cost
- Represents options, not requirements, for overall validation effort
  - Not all stages need to be performed
  - Some may not be feasible
- Iteration on TP capabilities at any stage
  - If fail or close to failing to meet requirements



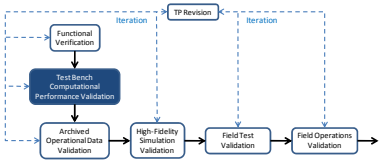
- Core techniques added at each stage
- Staged approach is a core technique

TP Validation Methodology:
Procedural Framework

- Functional Verification
  - Validation of functional requirements
    - Confirm TP functional response to specified inputs
  - Required if functional requirements exist
  - Performed prior to any performance validation tests

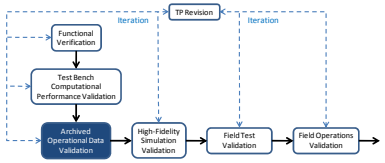


- Test Bench Computational Performance Validation
  - Validation of <u>direct</u> computational speed performance requirements
    - TP response time under specified conditions
  - Tests TP outside of client system (test bench)
  - Pro:
    - May be less expensive to run than full system tests
    - Requires just representative TP input data
    - Can be used for extreme condition testing
  - Con:
    - Necessary, but not sufficient for validation
      - TP performance typically impacted by system (e.g., shared processors)

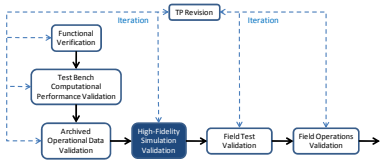


TP Validation Methodology:
Procedural Framework

- Archived Operational Data Validation
  - Validation of all performance requirements
  - Uses pre-recorded operational data (e.g., ETMS)
    - Input data for TP's client system
    - Actual aircraft trajectory data (for prediction accuracy requirements)
  - Pro:
    - Inexpensive way to validate feasible performance requirements
  - Con:
    - Impact of controller actions may limit feasibility
      - Example: Not useful for conflict false alert rate requirement
    - Not feasible if TP client system changes current operations

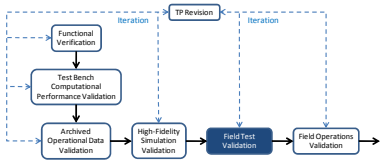


- High-Fidelity Simulation Validation
  - Validation of all performance requirements
  - Uses simulation of aircraft and/or operational environment
    - Too low fidelity impacts feasibility of validation tests
  - Pro:
    - Should be a feasible for most validation efforts
    - Enables statistically significant numbers of test cases to be run
  - Con:
    - Can be expensive
    - Knowledge and modeling of error sources required

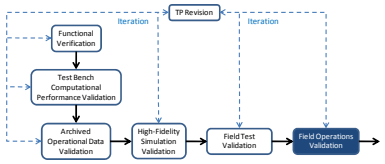


TP Validation Methodology:
Procedural Framework

- Field-Test Validation
  - Validation of all performance requirements
  - Near-operational conditions
    - In actual facility
    - Uses test procedures and/or test aircraft
  - Pro:
    - Can create future operational conditions with operational fidelity
    - Can test extreme or safety critical conditions
  - Con:
    - Often expensive
    - Limited number of test scenarios



- Field-Operations Validation
  - Validation of all performance requirements
  - Actual operational conditions
    - In actual facility
    - Uses actual procedures and aircraft
  - Pro:
    - Actual deployment environment, ultimate fidelity
  - Con:
    - Expensive
    - No control of environment, rare cases may not occur during testing
    - Difficult to capture large amounts of data for statistical significance
    - May limit to TP client systems that don't significantly alter current operations



ERAM Case Study:

FAA ERAM Validation Results

- FAA En Route Automation Modernization (ERAM) Factory Acceptance Test (FAT) in September 2007
  - Used pre-recorded data from Host Computer System and primary radars
    - Archived Operational Data and High-Fidelity Simulation (time-shifted archived data) Validation
  - 6 of 8 TP-related requirements not met
    - Two (level and non-level flight) altitude prediction accuracy requirements (direct) – not met
    - Two conflict probe warning time requirements (indirect) – met
    - Four conflict probe false alarm/missed alert rate requirements (indirect) – not met
- FAA initiated effort to correct ERAM deficiencies
  - Iterative modifications and re-evaluation performed
  - November 2008, ERAM passed all requirements
- Lesson Learned
  - Years of costly iteration (starting before FAT) required to ultimately meet requirements
    - Ad Hoc iterative procedures used
  - Approaches need improvement
- New methodology techniques could have helped!

ERAM Case Study:
Examples

- Paper presents several proposed techniques for improving ERAM validation approach
  - Analyses performed to determine, retrospectively, whether techniques would have helped
  - Used actual data from FAA FAT

- Two examples illustrate benefits of:
  - Iterating to achieve the level-flight altitude (LFA) accuracy requirement before validating other requirements
    - Technique: using validation stages
  - Identifying flights without lateral intent errors during false alarm rate testing
    - Technique: white box testing

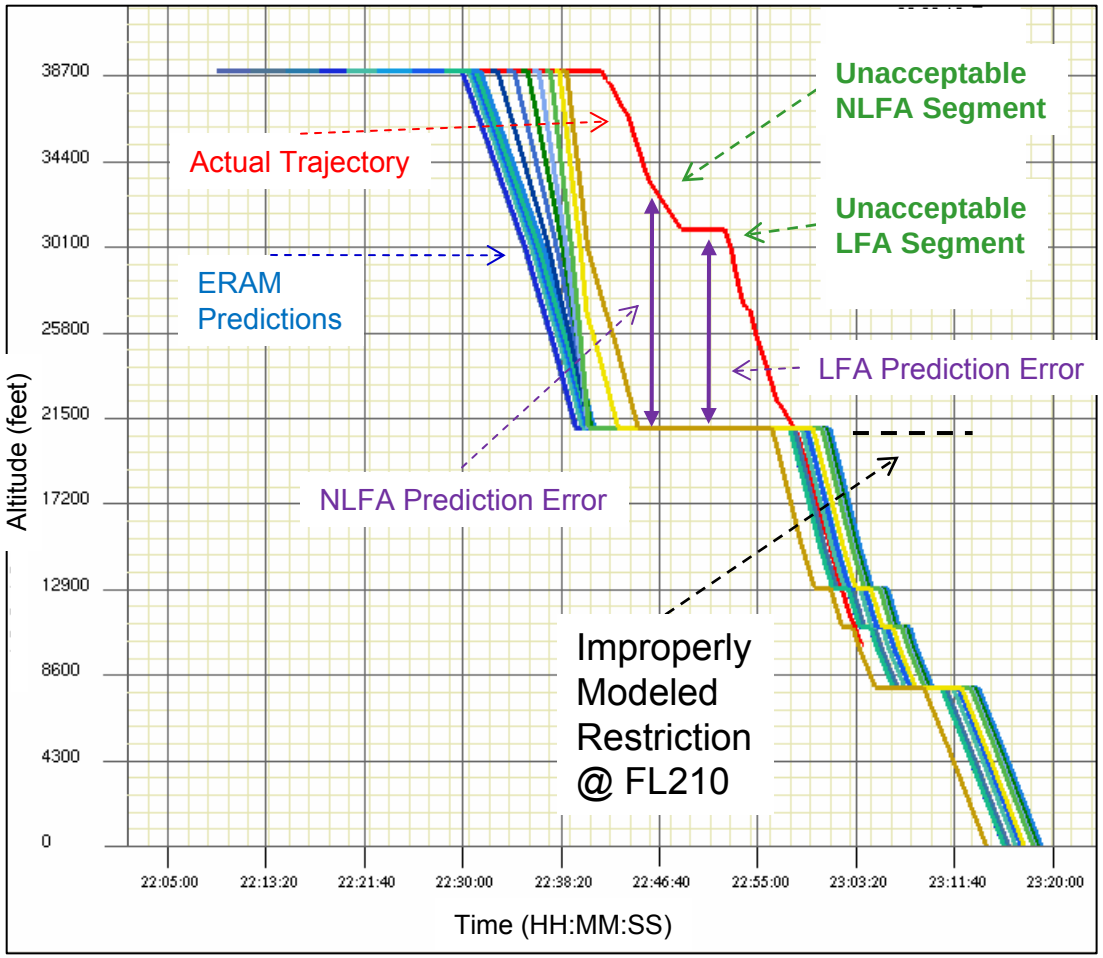
ERAM Case Study:
LFA Accuracy Requirement Example

- Validation Metric
  - If maximum prediction error >500 ft, level segment is unacceptable
  - Level flight accuracy metric: $LFM = \frac{\text{\# unacceptable LF segments}}{\text{Total \# LF segments}}$
- FAT results
  - Requirement: LFM ≤ 0.0016
  - Initial ERAM result: LFM = 0.0088 (unmet)
- Proposed Technique: Iterate to achieve LFA accuracy requirement before validating against other requirements
  - Analyze if would have improved meeting other requirements
    - Non-level flight (direct) accuracy (NLFA) requirement (unmet)
    - False Alarm Conflict probe (indirect) requirement (unmet)

ERAM Case Study:

LFA Accuracy Iteration Impact on NLFA Accuracy

- FAA post-FAT analysis identified:
  - Improperly modeled level-off restrictions
  - Impacted many flights in descent
- Impacts both LFA and NLFA accuracy
- Easier to identify in LFA accuracy analysis
- Iterating to meet LFA accuracy requirement would likely have improved NLFA accuracy performance

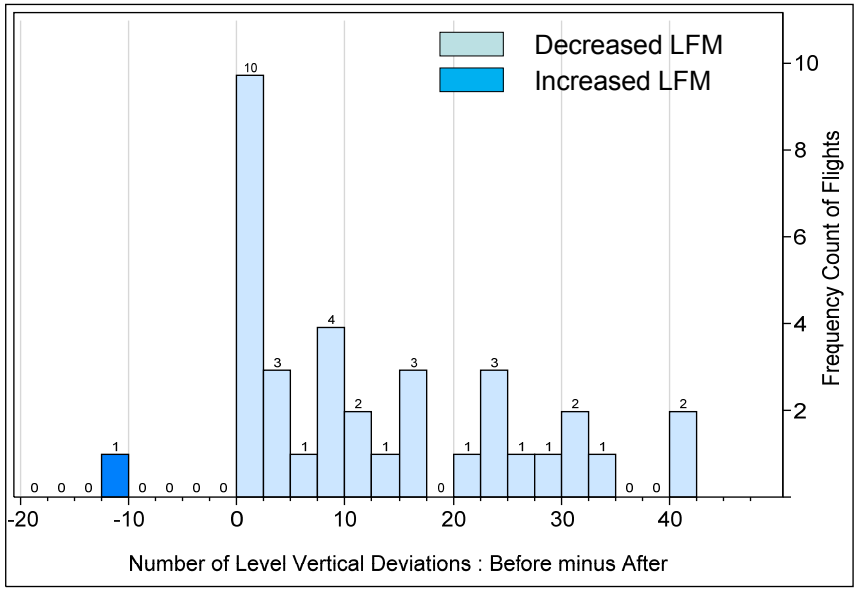


Example Flight: Vertical Profile (B737-700, cruising FL390 in ZDC)

ERAM Case Study:

LFA Accuracy Iteration Impact on False Alarms

- 36 flights had unacceptable LFA segments during FAT
  - Majority needed improvement to achieve post-FAT validation
- FAT results for these 36 flights
  - Flights with false alarms = 20
  - Number of false alarms = 36
- Post-FAT results for these 36 flights
  - Flights with false alarms = 12
  - Number of false alarms = 22
- Iterating to meet the LFA requirement would likely have improved false alarm performance



Post-FAT impact on 36 flights with unacceptable level flight altitude segments during FAT

ERAM Case Study:

Identifying Flights without Lateral Intent Errors Example

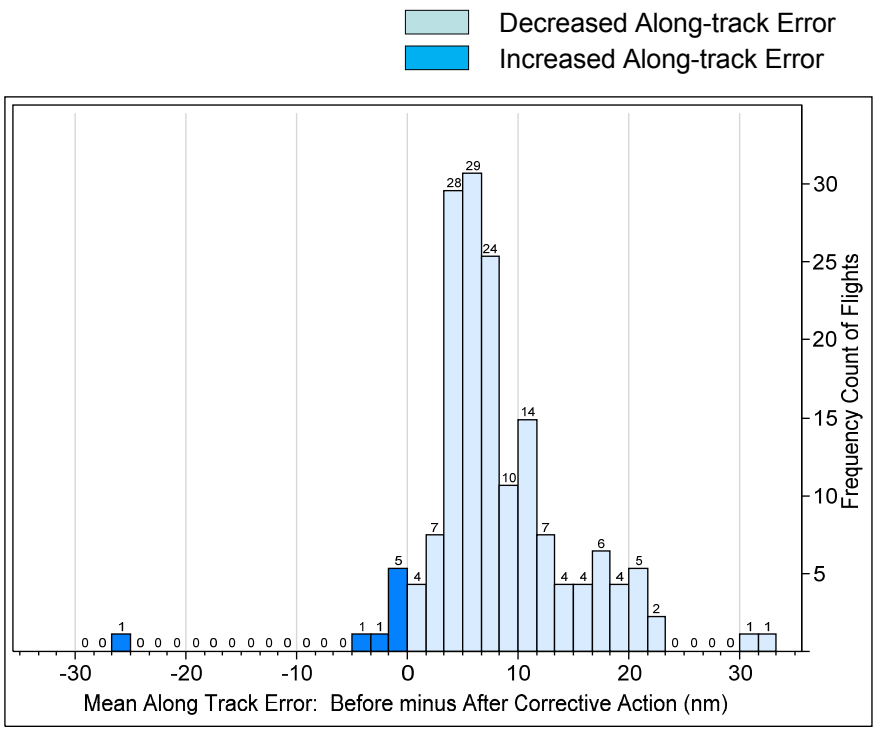
- Proposed Technique: Identify flights with and without lateral intent (routing) errors during false alarm testing
  - Analyze flights <u>without</u> lateral intent errors
    - Sufficient along-track lateral errors to require TP modification post-FAT?
    - Modifying TP for these flights had a positive impact on false alarm performance?
  - If so, approach would have
    - Identified along-track error impact on false alarms
    - Could have eliminated common error sources with lateral route error flights
      - Easier to resolve without lateral routing error impact

- Used lateral route adherence to identify flights without lateral intent errors
  - For each actual state (surveillance report), in adherence if:
    - Position within 1 nmi and heading within 30 degrees of flight plan route
  - Only required analyzing actual state and route data
    - No additional testing required
  - Effectively identified flights with primarily along-track lateral errors

ERAM Case Study:

Identifying Flights without Lateral Intent Errors Example

- Analyzed 158 in-adherence flights
  - Top 10% largest along-track errors
    - Majority of 158 flights were improved post-FAT to achieve validation
    - Along track error reduced
- Flights without lateral intent errors needed ERAM TP modifications to achieve validation
- Analyzed impact of these flights on false alarm performance
  - False alarms during FAT = 84
  - False alarms post-FAT = 58
- Iteration on these flights likely would have improved false alarm performance



Post-FAT reduction in mean along-track error (top 10% – 158 flights)

Concluding Remarks

- New TP validation methodology proposed
  - Core techniques and multi-staged approach
  - Designed to:
    - Reduce effort in identifying and resolving validation failures
    - Avoid costs associated with single-stage, pass/fail approaches
- ERAM case study analyzed
  - Illustrated new techniques could have benefitted ERAM validation by:
    - Ordering requirements to reduce overall effort
    - Identifying error sources during testing to provide TP iteration support
- Validation techniques could also support new TP R&D
  - New TP development
    - Rarely have direct TP requirements
    - Iteration typically required
  - New methodology adds structure to approaching these development issues