

## Project

# F-47 All-Source Navigation System Performance Validation

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## Background

The F-47 Navigation Computer has recently been upgraded with an Alternative Navigation Suite (ANS) designed to sustain navigation performance in contested, GPS-denied environments. The ANS augments the baseline GPS-inertial navigation solution with a set of Alternative Navigation (AltNav) aiding sources, including Magnetic Navigation (MagNav), Visual-Aided Navigation (VisNav), and Signals of Opportunity Navigation (SoPNav).

In normal operations, the ANS provides an integrated all-source navigation solution by fusing inertial measurements with GPS when available. When GPS is denied, the ANS is intended to maintain mission-useful navigation accuracy by transitioning to AltNav-aided operation, while continuing to provide integrity-relevant uncertainty outputs to support operational decision-making.

The program office has directed a Developmental Test (DT) evaluation to characterize navigation accuracy, inertial-only drift behavior, and integrity performance of the upgraded ANS under representative operational conditions, and to verify compliance with mission-relevant requirements.

Your DT team has been tasked to design and execute a statistically defensible evaluation of the upgraded F-47 Alternative Navigation Suite (ANS).

## Program Status

Hardware-in-the-Loop (HITL) testing of the upgraded Alternative Navigation Suite (ANS) has been completed. The HITL campaign evaluated navigation accuracy, filter stability, and fault-detection

behavior under representative flight dynamics and sensor conditions.

HITL analysis indicates that horizontal navigation error exhibits an approximate correlation time of 15 seconds during steady-state operation. This parameter provides the statistical foundation for estimating the effective independent sample size during flight testing.

In addition, the HITL campaign executed over 200 fault-detection events spanning multiple fault types (e.g., position step bias, position ramp bias, satellite-specific bias injection). Observed spoof-detect-reset cycle time averaged approximately 5 minutes per event, establishing the practical rate at which independent fault trials may be collected during flight.

Analysis of HITL results indicates that the most operationally stressing and detection-limiting case was the single-satellite ramp bias scenario, which produced the longest time-to-detect and greatest integrity exposure relative to other injected fault types. Consistent with a risk-based DT strategy, flight test will therefore prioritize evaluation of the single SV ramp bias case to verify that the upgraded ANS meets detection and integrity requirements under the most demanding credible fault condition.

The upgraded ANS is now ready for a dedicated Developmental Test (DT) flight program building upon the HITL results.

SPO and DT leadership have directed that flight evaluation utilize production-representative sensors and avionics bus data only. Dedicated high-rate flight test instrumentation (FTI) and internal fault flags will not be available. As such, fault-detection timing must be inferred from navigation solution behavior relative to known fault onset times and observed error growth.

Flight test resources are finite. Your DT team is responsible for planning, executing, and analyzing a statistically defensible flight-test campaign, including selection of operating modes, test durations, and fault-event allocation sufficient to support compliance assessment against program requirements.

## System Under Test

The System Under Test (SUT) is the F-47 All-Source Navigation System.

The ANS operates in the following modes:

- **AllSource Mode:** Inertial + GPS + AltNav fusion
- **AltNav Mode:** Inertial + AltNav fusion (GPS denied)
- **Inertial-Only Mode:** Pure inertial propagation

Available outputs include:

- Estimated position (LLH),
- Estimated position covariance (N-E-D),
- Estimated position integrity (N-E-D),

Truth position data (LLH) will be collected for performance assessments.

## Specifications

The F-47 ANS shall meet the following requirements.

### 1. Requirement 1: AllSource Accuracy

In AllSource mode:

- Horizontal position error shall be  $\leq 1.0$  m (95% confidence).
- Vertical position error shall be  $\leq 5.0$  m (95% confidence).
- Effective independent sample size  $N_{\text{eff}} \geq 300$ .

### 2. Requirement 2: AltNav Accuracy

In AltNav mode:

- Horizontal position error shall be  $\leq 5.0$  m (95% confidence).
- Vertical position error shall be  $\leq 10.0$  m (95% confidence).
- Effective independent sample size  $N_{\text{eff}} \geq 300$ .

### 3. Requirement 3: Inertial-Only Drift

In inertial-only mode:

- Horizontal drift rate shall be  $\leq 1.0$  NM/hr (upper 95% CI bound).
- Evaluation duration shall be at least 85 minutes.

### 4. Requirement 4: Fault Detection and Integrity

For 30 independent spoof events (SV ramp bias):

- At least 27/30 events shall satisfy:
  - Time-to-detect  $\leq 5$  s,
  - Horizontal HMI exposure  $\leq 1$  s during  $[t_0, t_D]$ ,
  - Vertical HMI exposure  $\leq 1$  s during  $[t_0, t_D]$ .

## Test Plan Excerpt

### STO 1: Evaluate Navigation Accuracy

Evaluate horizontal and vertical position error across ANS operating modes with statistically defensible confidence bounds.

**MOP 1.1:** Estimated horizontal and vertical error (meters) in AllSource Mode

**MOP 1.2:** Estimated horizontal and vertical error (meters) in AltNav Mode

### STO 2: Evaluate Inertial Drift Performance

Evaluate inertial-only horizontal drift rate over representative mission duration.

**MOP 2.1:** Estimated drift rate (NM/hr)

### STO 3: Evaluate Fault Detection and Integrity Performance

Evaluate single-SV ramp bias fault detection timing and integrity behavior.

**MOP 3.1:** Time-to-detect (seconds)

**MOP 3.2:** Horizontal and vertical HMI exposure time (seconds)

## Dataset Description

Returned datasets will contain:

- Time (seconds)
- True position (LLH)
- Estimated position (LLH)
- Estimated position covariance (N-E-D)
- Estimated position integrity (N-E-D)
- Fault onset times (for fault detection tests)

## Your Task

This project will be executed by the class as a single Developmental Test (DT) team. You are encouraged to organize into sub-teams aligned to individual requirements, with each team responsible for test design, analysis, and compliance assessment within its assigned area, while maintaining overall program-level integration and traceability.

### 1. Test Planning

As a class, develop a flight test plan sufficient to support statistically defensible compliance assessment.

- Determine required run durations sufficient to achieve  $N_{\text{eff}} \geq 300$  for steady-state accuracy evaluations using  $T_{\text{corr}} = 15$  s.
- Determine allocation of flight time across:
  - Inertial Only mode,
  - AllSource mode,
  - AltNav mode.
- Specify the number of fault events required to support Requirement 4 (5-minutes per spoof-reset cycle).
- Identify the ANS operating mode(s) in which fault detection testing will be conducted.
- Provide quantitative justification for all duration and event selections.

### 2. AllSource Accuracy Assessment

- Compute horizontal and vertical position error relative to truth.
- Estimate  $N_{\text{eff}}$  for the dataset using autocorrelation.
- Apply a defensible 95% statistical method (e.g., 95% CI on mean or 95th-percentile ECDF).
- Compare results to:
  - $\leq 1.0$  m horizontal requirement,
  - $\leq 5.0$  m vertical requirement.
- Explicitly state Pass/Fail determination.

### 3. AltNav Accuracy Assessment

- Compute horizontal and vertical position error relative to truth.

- Estimate  $N_{\text{eff}}$  for the dataset using autocorrelation.
- Apply a defensible 95% statistical method.
- Compare results to:
  - $\leq 5.0$  m horizontal requirement,
  - $\leq 10.0$  m vertical requirement.
- Explicitly state Pass/Fail determination.

#### 4. Inertial-Only Drift Assessment

- Compute horizontal position error versus time.
- Estimate drift rate as the slope of horizontal error versus time.
- Compute a two-sided 95% confidence interval on the slope parameter.
- Convert drift rate to NM/hr.
- Compare the upper confidence bound to the  $\leq 1.0$  NM/hr requirement.
- Explicitly state Pass/Fail determination.

#### 5. Fault Detection and Integrity Assessment

For each fault event:

- Identify fault start time  $t_0$  based on provided fault injection logs.
- Determine detection time  $t_D$  based on position error behavior.
- Compute time-to-detect:  $t_D - t_0$ .
- Compute horizontal and vertical protection levels using integrity covariance.
- Determine HMI occurrence (error exceeding protection level).
- Compute total horizontal and vertical HMI exposure during  $[t_0, t_D]$ .

Across all events:

- Apply the 27/30 compliance rule.
- Verify:
  - $t_D - t_0 \leq 5$  s,
  - Horizontal HMI exposure  $\leq 1$  s,
  - Vertical HMI exposure  $\leq 1$  s.
- Explicitly state Pass/Fail determination for Requirement 4.

#### 6. Preliminary Report of Results (PRR)

Present findings in a formal Preliminary Report of Results (PRR) consistent with Developmental Test review standards. The briefing shall include, at a minimum, the following sections:

##### (a) Executive Summary / BLUF

- Overall compliance determination for all four requirements.
- Key quantitative results supporting conclusions.
- Clear program-level recommendation.

##### (b) Test Design and Statistical Rationale

- Justification of selected run durations and operating modes.
- $N_{\text{eff}}$  calculations and statistical defensibility.

- Fault event allocation and independence justification.
- (c) **Requirement 1 – AllSource Accuracy Assessment**
  - Horizontal and vertical error analysis.
  - 95% statistical assessment method.
  - Explicit Pass/Fail determination.
- (d) **Requirement 2 – AltNav Accuracy Assessment**
  - Horizontal and vertical error analysis.
  - 95% statistical assessment method.
  - Explicit Pass/Fail determination.
- (e) **Requirement 3 – Inertial Drift Assessment**
  - Drift rate slope estimation.
  - 95% confidence interval on slope.
  - Explicit Pass/Fail determination.
- (f) **Requirement 4 – Fault Detection and Integrity Assessment**
  - Time-to-detect per event.
  - Horizontal and vertical HMI exposure per event.
  - 27/30 compliance logic.
  - Explicit Pass/Fail determination.
- (g) **Root Cause Analysis (if deficiencies observed)**
  - Technical explanation for observed shortfalls.
  - Discussion of filter tuning, geometry, covariance behavior, or detection logic as applicable.
- (h) **Overall Compliance Determination and Recommendation**
  - Overall compliance determination for all four requirements.
  - Key quantitative results supporting conclusions.
  - Clear program-level recommendation.

## PRR Assessment Rubric (20 pts)

PRR briefings will be evaluated using the criteria below. Each sub-item is scored binary: *Meets Standard* or *Does Not Meet Standard*.

- (a) **Problem Framing and Operational Context (2 pts)**
  - **Operational Framing (1 pt)** Frames the effort as verification of ANS performance under DT constraints (not merely data processing).
  - **Requirement Clarity (1 pt)** Clearly and correctly states all four governing requirements and associated statistical thresholds.
- (b) **Statistical Methodology and  $N_{\text{eff}}$  Justification (3 pts)**
  - **Correlation Time Application (1 pt)** Correctly computes correlation time to justify effective independent sample size.

- **$N_{\text{eff}}$  Computation (1 pt)** Correctly computes and reports  $N_{\text{eff}}$  for accuracy assessments.
  - **Statistical Confidence Method (1 pt)** Selects and correctly applies a defensible 95% statistical assessment method (e.g., 95% confidence interval on the mean or 95th-percentile ECDF), and justifies its appropriateness relative to the stated requirement.
- (c) **AllSource Accuracy Assessment (3 pts)**
- **Horizontal and Vertical Error Computation (1 pt)** Correctly computes horizontal and vertical error metrics.
  - **Confidence Comparison (1 pt)** Quantitatively compares 95% results to 1 m / 5 m requirements.
  - **Pass/Fail Determination (1 pt)** Clearly states compliance determination with supporting evidence.
- (d) **AltNav Accuracy Assessment (3 pts)**
- **Horizontal and Vertical Error Computation (1 pt)** Correctly computes AltNav horizontal and vertical error metrics.
  - **Confidence Comparison (1 pt)** Quantitatively compares 95% results to 5 m / 10 m requirements.
  - **Pass/Fail Determination (1 pt)** Clearly states compliance determination with supporting evidence.
- (e) **Inertial Drift Analysis (3 pts)**
- **Drift Rate Estimation (1 pt)** Correctly computes horizontal drift rate in NM/hr.
  - **Drift Rate Confidence Assessment (1 pt)** Correctly estimates horizontal drift rate as the slope of position error versus time, computes a two-sided 95% confidence interval on the slope parameter, and compares the upper bound to the  $\leq 1.0$  NM/hr requirement.
  - **Requirement Comparison (1 pt)** Clearly compares to  $\leq 1.0$  NM/hr requirement and states compliance.
- (f) **Fault Detection and Integrity Analysis (4 pts)**
- **Time-to-Detect Computation (1 pt)** Correctly computes  $t_D - t_0$  for each fault event.
  - **HMI Exposure Computation (1 pt)** Correctly computes horizontal and vertical HMI exposure per event.
  - **27/30 Event Logic (1 pt)** Correctly applies the 27/30 compliance rule.
  - **Integrated Pass/Fail Determination (1 pt)** Clearly states compliance with Requirement 4 and supports conclusion quantitatively.
- (g) **Communication, Traceability, and Recommendation (2 pts)**
- **Traceability and Figure Quality (1 pt)** All conclusions trace directly to quantitative results. Figures are readable and publication-quality.
  - **Executive Recommendation (1 pt)** Provides a coherent, defensible program-level recommendation supported by evidence.