VALIDATION OF ADVANCED SAFETY ENHANCEMENTS FOR F-16 TERRAIN FOLLOWING

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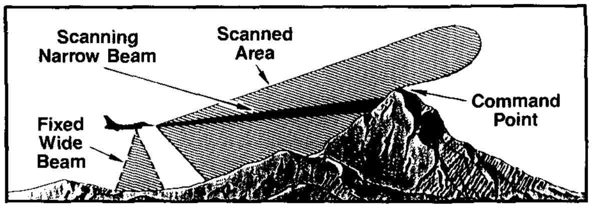
Abstract

This paper documents the verification approach used to validate System-Wide Integrity Management (SWIM) for its application to the F-16 terrain-following (TF) system in order to maximize flight safety during TF operation. This paper follows a paper presented to NATO-AGARD (North Atlantic Treaty Organization - Advisory Group for Aerospace Research and Development) in Cesme, Turkey, 25-29 April 1988, and published in November 1988 (AGARD Conference Proceedings No. 439, Software Engineering and its Application to Avionics), which documents the F-16 TF SWIM mechanization. This paper contains a brief summary of the results of the first paper followed by a strong justification for SWIM validation and the validation approach employed. Verification methods included stand-alone static and dynamic tests, integrated system tests, and flight tests. In particular, the failure modes evaluation testing (FMET) process is presented. In addition, safety, cost, and robustness benefits attributable to validation of SWIM for F-16 TF are covered.

Background

The limited room for on-board equipment in modern fighter aircraft has led to the mechanization of advanced flight-critical functions with nonredundant elements. For the F-16, such space limitations led to the mechanization of a TF system with multiple nonredundant sensors and control processors. In spite of lacking redundancy in critical subsystems, flight safety concerns required that fault tolerance had to be achieved in the overall TF system.

As a result, development of the F-16 TF system was accomplished with an advanced flight safety enhancement technique — SWIM. SWIM is a new approach to both the design and utilization of in-flight built-in test (BIT) to detect otherwise undetectable malfunctions that could result in the loss of an aircraft. SWIM was first developed by General Dynamics for its Advanced Fighter Technology Integration (AFTI) Program and for the Automated Maneuvering Attack System (AMAS). SWIM was then applied to the F-16 TF system. F-16 TF system operation consists of low-level flight during day, night, or adverse weather conditions at a fixed offset over terrain while operating within aircraft and crew acceleration constraints. F-16 TF is summarized in Figure 1 and its architecture is depicted in Figure 2. The TF subsystems are the combined altitude radar altimeter (CARA); low-altitude navigation and targeting infrared for night (LANTIRN) navigation pod, which contains the terrain-following radar (TFR); inertial navigation system (INS); central air data computer (CADC); head-up display (HUD); global positioning system (GPS); digital flight control system (DFLCS); and the core avionics that include the fire control computer (FCC), stores management set (SMS), multifunction display (MFD), and multiplex bus (MUX) connecting the subsystems. Detection of flight-critical malfunctions by SWIM is followed by an automatic recovery maneuver that consists of a roll to wings-level fly-up for the F-16 TF system.



- **Forward-Looking Radar Senses Terrain and Associated Computer Generates Climb/Dive Commands**
- **Flight Control System Commands Aircraft State Change Based on Commands from Radar Computer**
  - **— Direct Coupling in Automatic Terrain Following (TF)**
  - **— Control Stick Coupling of Displayed Commands in Manual TF**
- **Subsystems Feedback Changing Aircraft State for Command Nulling and Radar Scan Stabilization**
- **Radar Altimeter Controls Aircraft Over Low Back-Scatter Terrain and Checks Operation During Forward-Looking Radar Control**

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Figure 1 Terrain Following Requires Integration of Multiple Subsystems

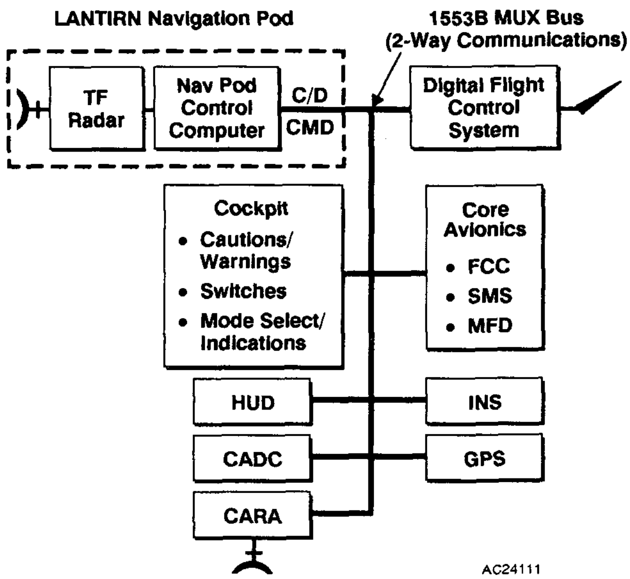

Figure 2 F-16 TF System Architecture

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SWIM Definition

A brief definition of SWIM is self-test of a function, as opposed to traditional self-test of a single subsystem. Figure 3 illustrates the SWIM technique, which is system wide in that it includes all individual subsystems and interfaces involved in that function (left circle). SWIM involves an independent monitor site (center circle), i.e., the F-16 TF DFLCS.

these existing networks had ready access to the required function parameters, as does the F-16 DFLCS via the 1553B MUX bus, implementation of SWIM monitors would be a relatively minor task. The fault-tolerant structure for the F-16 TF SWIM monitors already existed. All that was necessary was to add the monitor algorithms to the existing cross-channel communication and voting planes through a software modification to the DFLCS Operational Flight Program (OFP). Figures 4 and 5 are illustrations of the F-16 quad-redundant DFLCS and its associated redundancy management, respectively.

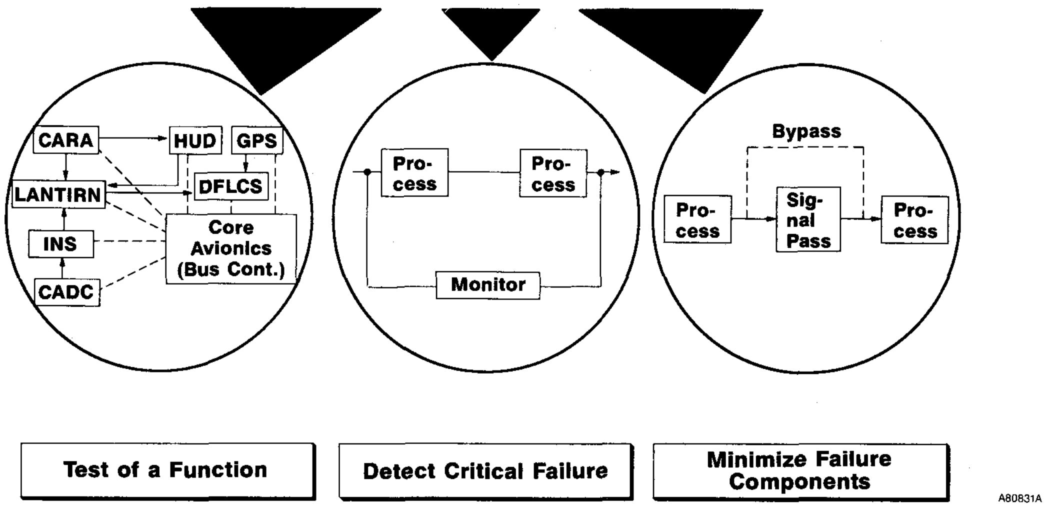


Figure 3 System-Wide Integrity Management

The management aspect is applied in the SWIM design phase; it involves the elimination of a safety impact associated with a particular subsystem failure rate when that subsystem has minimal involvement in the function (as in the right circle of Figure 3). In other words, the function under consideration, TF in this case, has certain parameters or signals that are safety critical in that undetected aberrations in these signals can result in aircraft loss. If one of these safety-critical signals is involved minimally in a subsystem or simply routed through that subsystem, then SWIM management involves designing the SWIM monitor architecture to rely on an alternate route or bypass for that signal to ensure detection of failures in that subsystem that affect the critical signal. The safety impact of that particular subsystem is then effectively bypassed. The bypass eliminates safety impact associated with failures of that subsystem since failures of that subsystem are detected by comparison with an alternate source of the same signal.

SWIM Host Site Requirements. An independent monitor site for F-16 TF SWIM could conceivably have involved any processor with sufficient memory, throughput, and access to critical data sources. However, one implicit requirement of the SWIM host site is that monitor execution must have a dependability far greater than the elements being monitored. Otherwise, SWIM integrity would be degraded by nuisance trips or by failure to always detect critical malfunctions.

Based on this extreme dependability requirement to preclude undetected latent failures of SWIM monitors, the SWIM monitors were hosted in a fault-tolerant processing network. Such networks carry with them the cost associated with redundant physical components as well as the cost of developing robust failure management schemes for the fault-tolerant network. Fortunately, modern digital flight control systems, like those on the F-16, already have such a fault-tolerant network in place to ensure extreme dependability because of the flight-critical aircraft control functions computed by the processor network. If

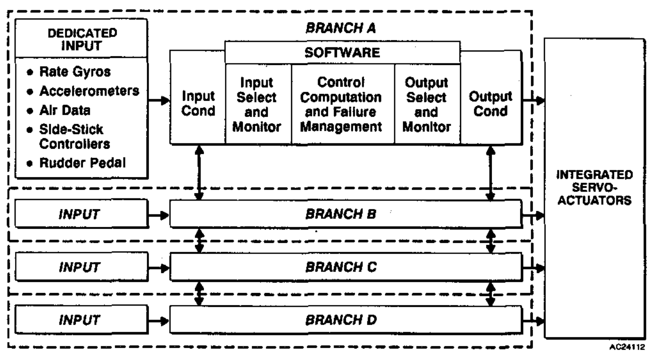


Figure 4 F-16 Digital Flight Control System

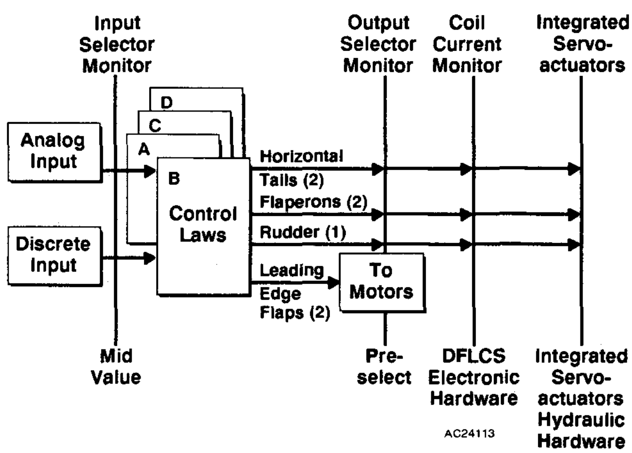


Figure 5 F-16 Digital Flight Control Redundancy Management

F-16 TF SWIM Features. Figure 6 is a listing of the 12 features or monitors that make up F-16 TF SWIM. SWIM features are categorized by type of malfunction they cover. SWIM drift and bias error features monitor the INS and LANTIRN navigation pod for attitude and inertial velocity corruption not detectable by subsystem self-tests. Utilization of a DFLCS software attitude estimator, a GPS-based inertial velocity source, and a CARA-based low-altitude check enables detection of such hazardous fly-low drift and bias conditions. Subsystem processor malfunction detection is provided by CARA status monitors, comparison of CARA altitude from the CARA receiver-transmitter versus the altitude from the CARA signal data converter, and cyclic test problems with predetermined proper results run in the LANTIRN navigation pod with results output to the DFLCS. The communication path loss features prevent undetected communication loss via (1) MUX terminal to MUX terminal transmission and receipt verification, (2) redundant status and integrity discretes that are provided independent of the MUX bus, and (3) an auto-TF engagement verification to prevent the pilot from relinquishing vertical clearance control to a disengaged auto-TF system.

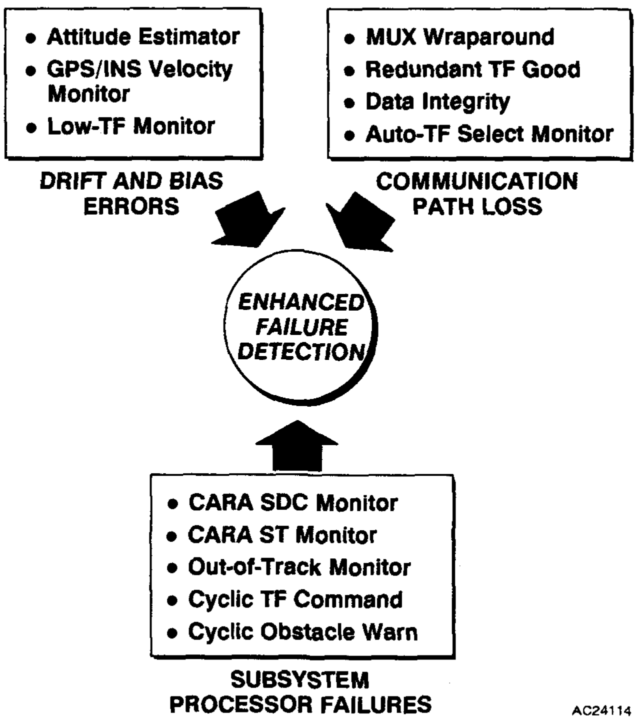


Figure 6 F-16 SWIM Features Cover Different Undetected Malfunctions

F-16 TF SWIM Improvement and Cost Effectiveness. The SWIM safety improvement and cost effectiveness of achieving those safety improvements noted in the earlier NATO-AGARD paper (November 1988) are illustrated in Figures 7, 8, and 9. Comparisons of the predicted mishap rate reductions of 14 percent for F-16 TF SWIM and 17 percent for traditional redundancy from Figure 7 with the Figure 8 costs of \$2 million for F-16 TF SWIM and \$100 million for traditional redundancy yields the Figure 9 cost effectiveness data. As indicated in Figure 9, the mechanization of SWIM for F-16 TF with its single-thread system is 47 times more cost effective than traditional TF with its redundant INS and CARA.

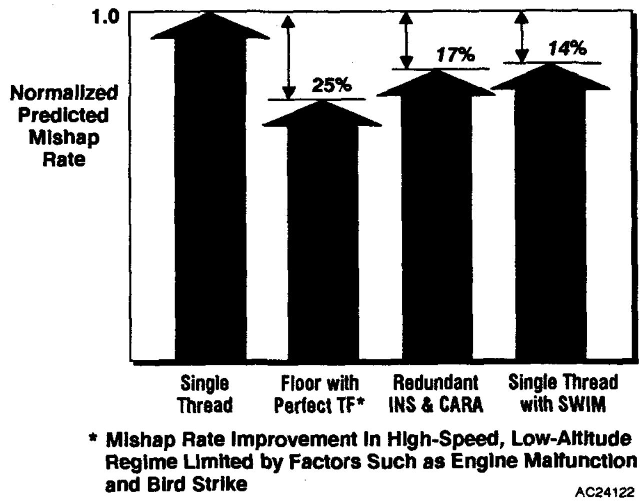


Figure 7 F-16 Predicted Mishap Rate Reduction

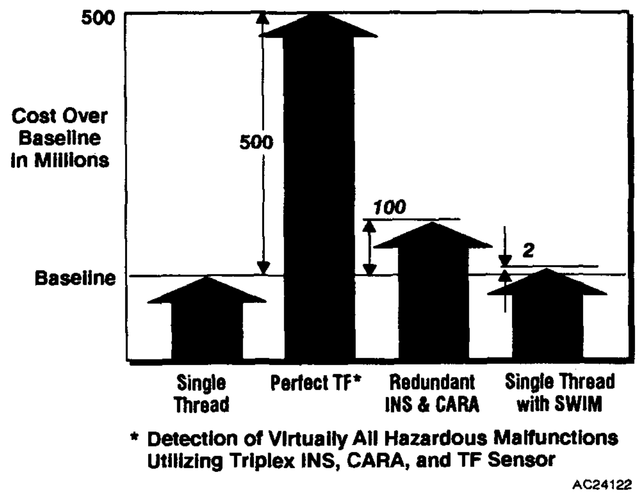


Figure 8 Alternate F-16 TF System Cost

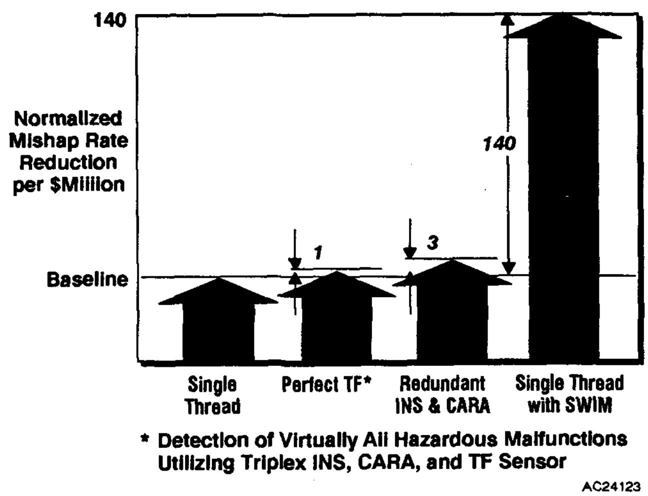


Figure 9 Alternate F-16 TF System Cost Effectiveness

Background Chronology. Figure 10 graphically displays the background leading to the current paper on F-16

TF SWIM validation. Though the SWIM concept originated in the F-16 AMAS Program, it was not until the F-16 TF Program, with its charter for implementation of a production system, that more stringent qualification and validation requirements had to be met than for the one-of-a-kind, F-16 AMAS flight demonstration program. The first F-16 TF SWIM paper covered development of F-16 TF SWIM, while this paper focuses on the validation of F-16 TF SWIM using a phased laboratory ground test and flight test approach to thoroughly validate all aspects of F-16 TF SWIM as denoted in Figure 10.

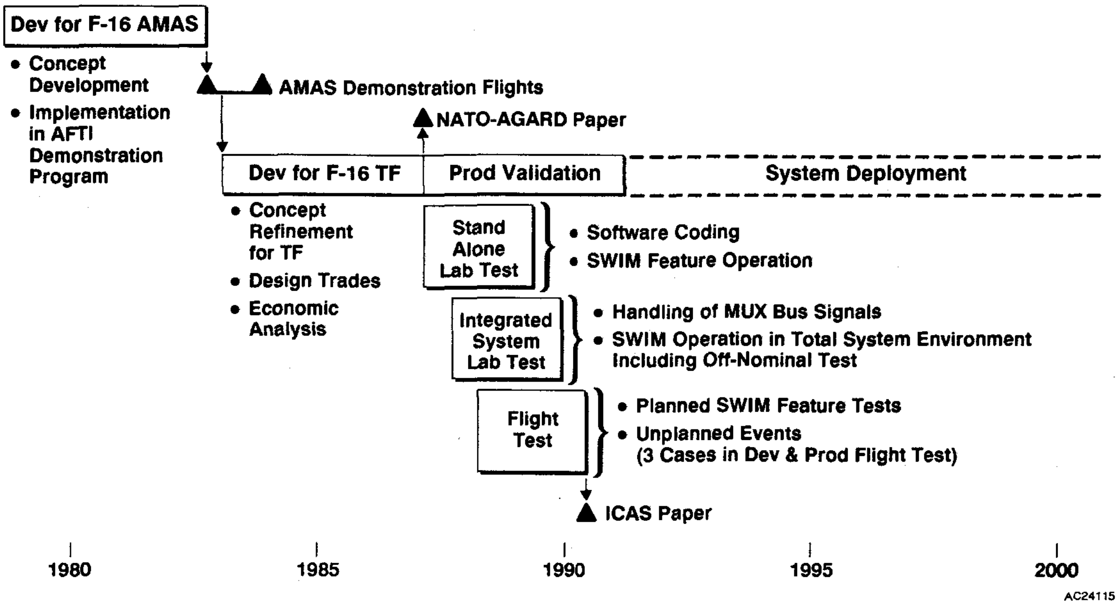


Figure 10 General Dynamics SWIM Chronology

itors (1) operate properly to detect hazardous malfunctions in a timely fashion and (2) do not trigger excessive false-alarm automatic fly-ups. Monitor thresholds and annunciation delays had to be set tight enough to catch all hazardous failures but loose enough to allow for noise, error tolerances, and short transient conditions without generating a recovery maneuver. Though the SWIM design prior to validation was intended to provide a dependable method of covering all hazardous failures without nuisance false alarms, only laboratory and flight test verification could guarantee that the design goal was actually achieved. TF is a flight-critical function in that undetected malfunctions could result in aircraft loss. TF is also a mission-survivability function in that maintaining low altitude (impossible with excessive false-alarm fly-ups) is necessary to prevent attrition by surface-to-air weaponry. Because of both the flight-criticality and

Reason for SWIM Validation

To reap the predicted mishap-rate reduction and cost-effectiveness benefits just summarized, validation of the SWIM features was necessary. Validation would ensure (Figure 11) that the individual SWIM features or mon-

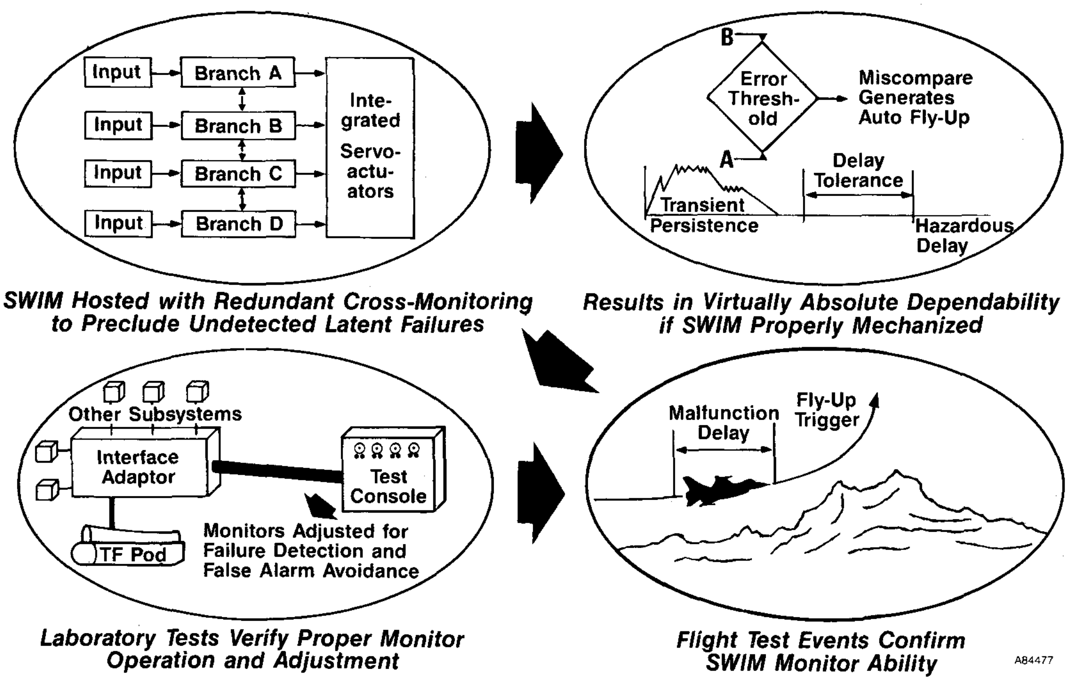


Figure 11 Need for Validation of SWIM Features

mission-survivability aspects of TF, SWIM features had to be finely tuned to ensure both timely malfunction detection and avoidance of nuisance false alarms.

Validation Methodology

As depicted in Figure 11, SWIM feature validation involved laboratory testing prior to flight tests. SWIM laboratory tests were also used to validate critical failure detections that could not be verified in flight test. These failures were of the hardware type where breakout boxes were used to inject failures within the hardware during operation in a closed-loop set-up. A matrix of failures was generated in the test plan and the expected results of the initiated failures were listed. In general, the expected results were terrain-following termination and an automatic roll to wings-level fly-up. For flight test, specific events were planned where the airplane would violate a condition such as above-ground altitude and cause a fly-up. Figure 12 is a summary of the basic three-phase approach to SWIM validation employed for F-16 TF. The first two phases, stand-alone tests and integrated system tests, constituted the ground laboratory testing and were followed by the actual TF flight test phase.

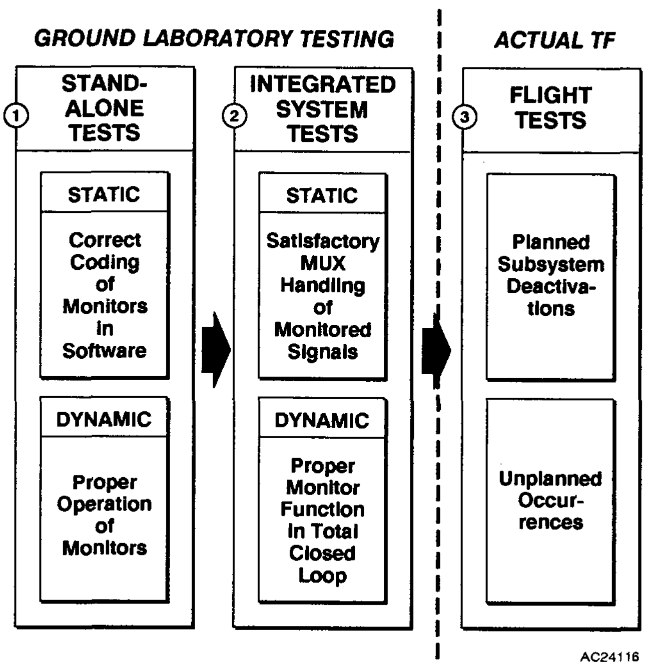


Figure 12 SWIM Validation Process

In performing the ground laboratory verification tests, validating the SWIM features in a closed-loop set-up with as many as possible of the actual TF subsystems was important. All of the TF subsystems were considered for actual subsystem use in the closed-loop configuration; however, some of the closed-loop subsystems were simulated instead because (1) they were not directly involved in any flight-critical algorithms and computations and (2) actual subsystem use would have significantly increased the complexity and difficulty of developing the laboratory validation set-up for negligible increase in fidelity of the results. Also, TF operation effects of those subsystems that were simulated, based on extensive analyses and laboratory testing, consisted of relatively straightforward input/output (I/O) signal changes such as signal presence or absence, fixed-bias shifts, pass-throughs, or simple manipulations. The effects of other TF subsystems that involved more complex treatment or generation of flight-critical TF signals could not be accurately predicted. For these more complex computation subsystems, actual hardware and software were used because of the difficulty of providing an acceptable simulation model and because of the criticality of the subsystem to TF operational safety.

The resulting closed-loop laboratory TF configuration constitutes a realistic tool for verification of a complete actual TF system prior to flight test. Subsystems or portions of the laboratory TF closed-loop set-up were implemented as detailed in Figure 13. The test configuration for laboratory TF testing is illustrated in Figure 14 with the diagonally-hatched boxes indicating actual hardware.

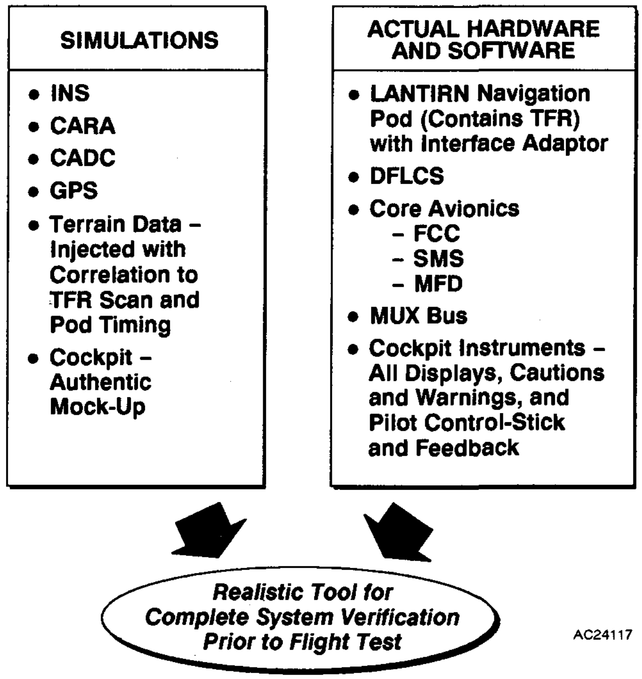


Figure 13 Closed-Loop Laboratory TF Elements

The actual validation tests of the SWIM features included both extensive ground laboratory testing and flight testing. Ground laboratory testing was performed in two phases for a total three-phase approach (Figure 12). Validation testing was structured in a manner (1) to identify and resolve SWIM feature design and requirement errors at the lowest possible level of the system test program, (2) to exercise TF system fault-tolerance with off-nominal testing in a controlled laboratory environment with flight hardware prior to flight testing, and (3) to evaluate modifications or refinements to the SWIM monitors or peripheral functions such as cockpit feedback that occurred during the development program. These efforts ensured that undesired changes were not introduced.

Stand-Alone Tests

Stand-alone testing consisted of both static and dynamic phases. Since the addition of the SWIM monitors was accomplished primarily by the modification of several existing OFPs, stand-alone testing focused on the verification of OFPs and integration in their respective processors. Stand-alone static tests were performed first to identify discrepancies at as low a level as possible by verifying correct coding of all new and modified software modules and functions prior to requirements verification.

Stand-alone dynamic tests were conducted to verify requirements by demonstrating proper operation of the

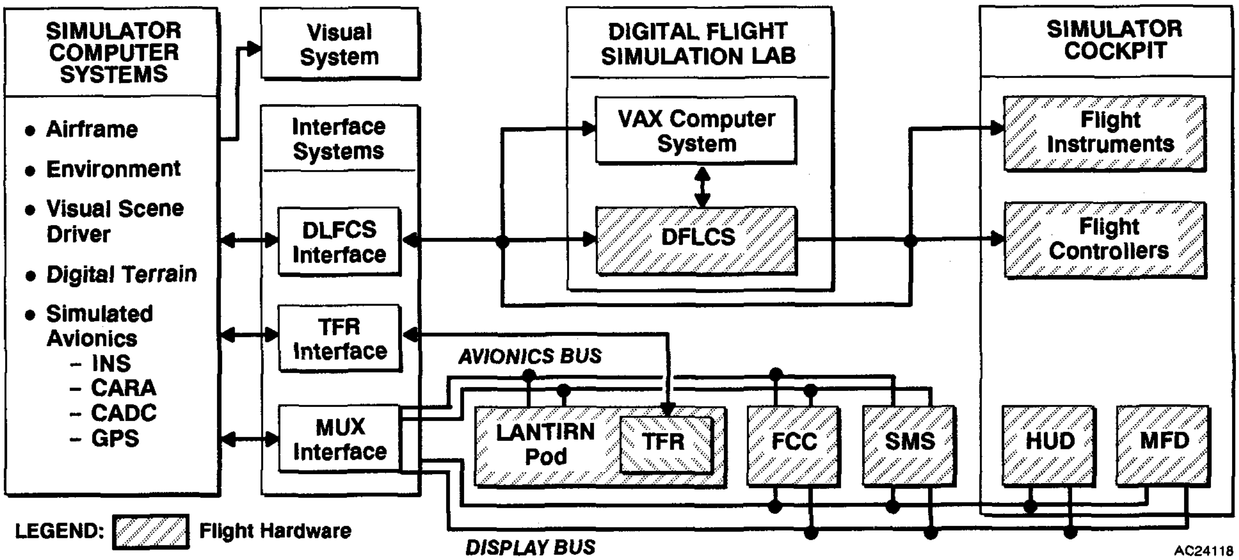


Figure 14 Laboratory TF Test Configuration

SWIM monitors with the subsystem OFP resident in the actual subsystem hardware with various simulated inputs. All software-controlled fault detection monitors were exercised with simulated system or hardware failure inputs. Regression tests of requirements were conducted by selection of a core set of test cases that stressed all functions, i.e., both those that were modified as well as those that were unmodified, and additionally selected test cases that could be used to evaluate peculiar changes to modified functions. These test criteria were applied to all of the OFPs modified to incorporate SWIM monitors.

Integrated System Tests

The integrated system testing was intended to evaluate the SWIM design requirements and operational acceptability, integrity, and performance in an integrated closed-loop environment. Since the test configuration was a controlled environment, analyzing the SWIM design during both normal dynamic and error-induced TF flight was quite simple. Tests were conducted to evaluate many factors such as MUX interface compatibility, persistence timing, tolerance effectiveness, subjective human factors assessments, and TF performance tests. Integrated system testing consisted of both extensive static and dynamic phases and included specific mechanization detail evaluations and integrated system validation (ISV). Failure modes evaluation testing (FMET), a specialized test area to verify coverage of hazardous failures, and ISV, used to verify proper OFP operation, were key elements employed in integrated system testing. Integrated system testing verified expected performance and operational acceptability of the SWIM monitor design.

Integrated static tests of various F-16 TF system components were used to evaluate interfaces in real time with the functional processors in an open-loop mode and operating off static input. These static tests focused on the verification of MUX bus message traffic and analog and discrete interfaces. Because of the distributed processing architecture of the TF system, SWIM monitors rely heavily on information conveyed over the MUX bus. Static tests provided confirmation of the MUX bus message formats and content for use by the distributed processors.

Integrated dynamic tests encompassed a real-time, closed-loop evaluation of the F-16 TF system in the laboratory environment to verify proper SWIM monitor operation in a total system environment prior to flight testing. The integrated dynamic test environment provided synchronized loop closure of the DFLCS and the TF radar processing system, with flight-hardware-driven displays in the simulator cockpit. The closed-loop laboratory configuration for integrated dynamic testing included all key TF components with loop closure and display as shown in Figure 13. Integrated dynamic testing was the first test level that provided confirmation of SWIM feature operation in a total system environment. As stated previously, the TF system distributed processing environment results in many SWIM monitors relying on dynamic information passed between processors. Critical timing, mode selection, and data-phase selection of the monitors could not be verified without the closed-loop integrated dynamic test phase of integrated system testing.

Of special note is the loop closure of the TF processor. By breaking the interface of the radar processor analog and digital processing sections, the simulation computer fed the scanned data into the radar processor, while the radar processor fed the simulation computer the angle and scan pattern for the next terrain data. The simulation computer performed the aircraft state computations and coupled the results of these computations with the generation of the radar scan bars from the terrain data base.

As a final step under the integrated dynamic test phase of integrated system testing, ISV was performed to evaluate the dynamic performance of the F-16 TF system and SWIM mechanization. ISV validated the acceptability of the flying qualities and safety mechanization of the integrated system in a real-time, closed-loop evaluation. ISV assessed the TF system algorithms and SWIM monitors for safety and operating performance to ensure overall system behavior before flight. ISV involved performing simulated aircraft maneuvers and pilot functions while in, out of, and transitioning through the TF operating envelope over various terrain types with multiple aircraft loadings. Clearance for actual flight could only be considered after completion of ISV with satisfactory resolution of any safety-related discrepancies revealed during ISV. Pilot evaluations were also used in ISV to provide an independent assessment of the SWIM monitor design. The pilot tested the monitors' function during typical and atypical flight operations and determined pilot usability and acceptability.

Failure Mode Evaluation Testing. One of the primary objectives of the dynamic testing of integrated system testing was verification of proper SWIM mechanization in a realistic total-loop system environment prior to flight testing. This objective was accomplished by conducting FMET. FMET is concerned exclusively with possible hazardous failures or malfunctions that the TF system might encounter and the ability to detect and recover from those hazardous malfunctions. FMET is of particular importance in that it provides operational confidence in the SWIM features prior to flight testing. This demonstrated capability and resulting confidence significantly reduced the number of flight tests required since extensive reflights for tuning of SWIM features were not required. To accomplish the FMET objective, a representative set of hazardous cases was selected that would exercise all of the F-16 TF SWIM features and thereby provide confidence in the capability of the SWIM design to respond to all hazardous malfunctions with appropriate failure annunciations and an automatic recovery maneuver. FMET testing also provided a system performance demonstration in a low-altitude failure environment.

In selecting the types of failure modes to be included in FMET, three categories were chosen. The first failure category chosen provided a limited evaluation of each of the SWIM monitors within the DFLCS. These failures were, in most cases, inserted via the host simulation computer. Biases, ramps, and bad status words were sent to the DFLCS over the MUX from the simulated subsystem (INS, CARA, LANTIRN navigation pod) to validate the operation of the SWIM monitors. Test cases included in this category are shown in Figure 15 under the design requirements caption.

The second category of failure modes includes failures internal to the TF system (DFLCS, LANTIRN navigation pod and core avionics). These test cases were designed to evaluate the ability of the TF system to safely withstand failures. These failures were inserted into TF critical systems by causing actual hardware failures within the system at crucial functional areas, by removing power to specific subsystem functions, or by failing connections between significant hardware devices. Included in this category were failures of the MUX bus communications. The failure cases tested in this category are shown in Figure 15 under the robustness caption.

The final failure category was designed to validate the detailed design assumptions made during the design process. Design aspects such as algorithm limits, persistence counters, and system bias threshold levels were modified as a result of FMET to ensure reliable SWIM monitor response and to prevent false-alarm activations. As an example, failures were inserted by the simulator operator via the simulator interface program to induce biases into various INS signals received by the DFLCS and other subsystems over the MUX. Bias values were chosen to validate SWIM monitor tolerance thresholds specified by the design team. Test cases included in this category are listed in Figure 15 under the thresholds and persistence caption.

Failures were inserted into critical subsystems via specially designed failure harnesses and circuits. For each test case, results were recorded along with all pilot comments. Other data collected for each case included aircraft response data and fault reporting information. Discrepancy reports were written for all observations in

DESIGN REQUIREMENTS

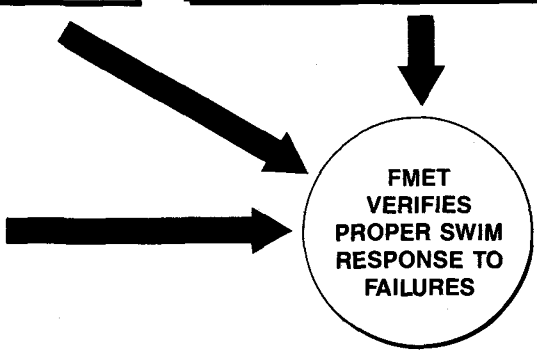
DESIGN REQUIREMENT	FAILURE DESCRIPTION
Drift and Bias Errors*	Pitch or Roll Bias
	INS and GPS Velocity
	SDC and Pod Monitor
Subsystem Processor Failures*	SDC Data and Status
	CARA Self Test Status
	CARA Signal Tracking
	Climb/Dive Test
	Obstacle Warn Test
Communication Path Loss*	Terminal and DFLCS Line
	Loss of TF Good
	Subsystem Self Test or Freshness
	Fail to Engage Auto TF

THRESHOLDS AND PERSISTENCES

MONITOR RESPONSE	FAILURE DESCRIPTION
Detection of Error Tolerance Exceedance After Delay to Avoid False Alarms from Transients	Inertial Velocity Errors Over Tolerance
	Attitude Errors Over Tolerance
	Altitude Above Ground Level Below Threshold

ROBUSTNESS

TF ROBUSTNESS ASPECT	FAILURE DESCRIPTION
SMS Backup Bus Control	FCC Deactivation
TF with Single AMUX	One Branch of Dual AMUX
TF With Dual Failures in DMUX OR Quad-Redundant DFLCS	DUAL FAILS: DMUX, Air Data, LEF Lock, Angle-of-Attack, Normal Acceleration, Horizontal Tail, I/O Control, A/D, DFLCS Branch, Power Supply



** Tests Corresponding SWIM Features from Figure 6*

Figure 15 FMET Failure Category

which actual test results differed from expected results. All resolutions to these discrepancies were verified by documentation and retest before the next phase of demonstration testing. Using the cockpit simulator capability, pilots and engineers flew the complete matrix of the selected TF failure modes to validate satisfactory handling of these failures. More specifically, system operation during and following the insertion of a failure condition in the system was evaluated to verify generation of the expected cautions, warnings, pilot and maintenance fault lists (PFLs/MFLs), and automatic fly-ups.

FMET was accomplished in two phases; the first phase was the extensive engineering testing of the selected failure modes inserted in real time at critical points in defined flight profiles. The second phase, i.e, pilot demonstrations, was conducted using several qualified pilots in the simulator to fly a subset of "worst case" scenarios. Pilot evaluations were used to verify proper aircraft system response in the presence of injected failures, to obtain the pilot's interpretation of failure modes effects, to evaluate SWIM monitor design, and to assess pilot and aircraft capabilities to safely respond to and interpret the failure. The pilot was then allowed to fly unplanned scenarios that allowed the pilot to evaluate failure effects in a scenario the pilot considered important. After completion of the FMET exercise, the pilots were interviewed and their recommendations documented and used to change the SWIM monitor design or to redesign the failed subsystem to eliminate the failure mode.

Flight Tests

Flight test was the final aspect of the SWIM validation process. SWIM features were exercised during controlled in-flight test scenarios. Flight test objectives were to (1) validate SWIM response in the presence of selected simulated failures, verifying that the response is similar to laboratory results recorded from the FMET exercise, and (2) determine pilot acceptability and adaptability to the work load level associated with the SWIM mechanization and the integrated pilot/vehicle interface. Planned subsystem failures were simulated by removing power to selected TF system components and by performing aircraft maneuvers that violated TF operational limitations. Simulated failures demonstrated the SWIM response to failures that should be detected within the TF operational envelope. Preplanned maneuvers were conducted to demonstrate aircraft response to unannounced system failures. Preplanned aircraft maneuvers were performed with the pilot providing override commands that resulted in violation of TF operational envelope parameters such as vertical clearance warning, dive angle, roll angle, and obstacle warn limits. In all cases, the tests were conducted to confirm that the appropriate SWIM monitors responded to abort unsafe TF flight via the automatic fly-up recovery maneuver.

In addition to the planned subsystem failures, unplanned events occurred during flight testing that provided additional confirmation of SWIM features. In these unplanned events, subsystem malfunctions occurred that were neither detected nor flagged by the individual subsystem self-test. However, the relevant SWIM monitors did detect the malfunctions and trigger the appropriate responses for the events detailed in Figure 16. These unplanned failure detections by the SWIM features constituted positive proof of the value of SWIM, even during development flight testing prior to production deployment to user field bases.

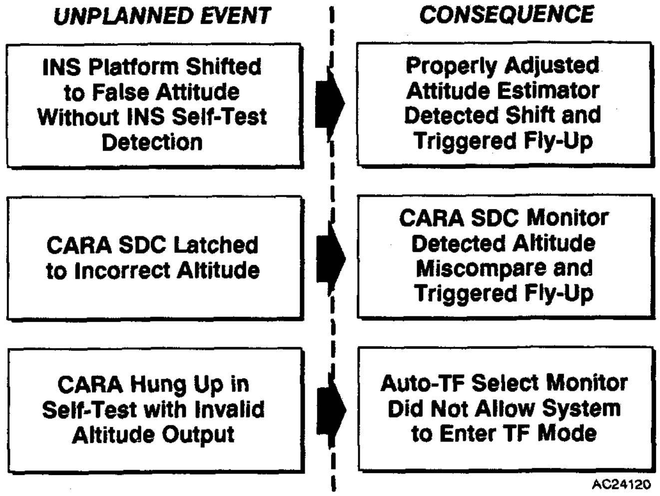


Figure 16 Unplanned Flight Test Events Confirm SWIM Capability

SWIM Validation Benefit

Extensive ground and flight test validation used to prove the F-16 TF SWIM features resulted in a TF function with the highest achievable level of safety for the F-16 TF equipment configuration. Figure 17 is a summary

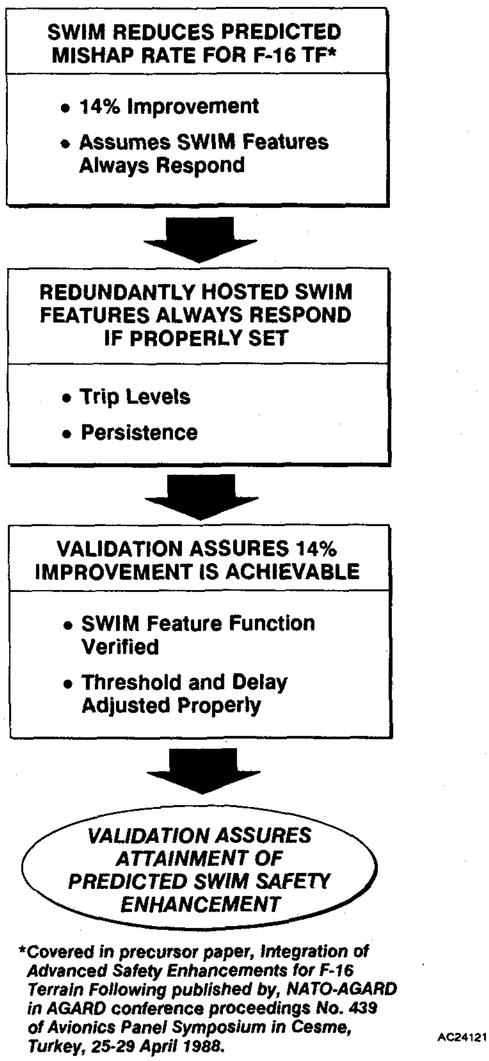


Figure 17 Safety Benefit Attributable to SWIM Validation

of the safety benefit attributable to the SWIM validation process. The TF safety benefit was also attained without compromising operational usability that would have occurred if there were excessive monitor activations with ensuing automatic recovery maneuvers. The process of stand-alone testing and integrated system testing with FMET verified the capability of the SWIM features to respond to all hazardous malfunctions that they were designed to detect while including the adjustment of SWIM feature trip thresholds and persistence criteria prior to flight testing.

SWIM feature verification and adjustment prior to the final flight test validation resulted in a reduced number of test flights; 125 for the F-16 auto-TF development program compared to 250 for the original F-111 auto-TF development program. The reduced number of F-16 test flights was a consequence of very few reflights for SWIM feature refinement or tuning, since the SWIM monitors were all functional as designed with proper trip levels and persistences due to the comprehensive ground testing with FMET. The F-111 program did involve limited ground interface and integration checks, but nothing approaching the extensive F-16 SWIM validation process. Consequently, many more flights were used to adjust or tune thresholds in the F-111 traditional redundancy comparison monitors. Figure 18 is an illustration of the cost benefit attributable to SWIM validation. One can see that a 50-percent reduction from $25 million to $12.5 million was achieved with the F-16 SWIM validation process over the F-111 approach that involved extensive reflights to tune traditional-redundancy comparison monitors.

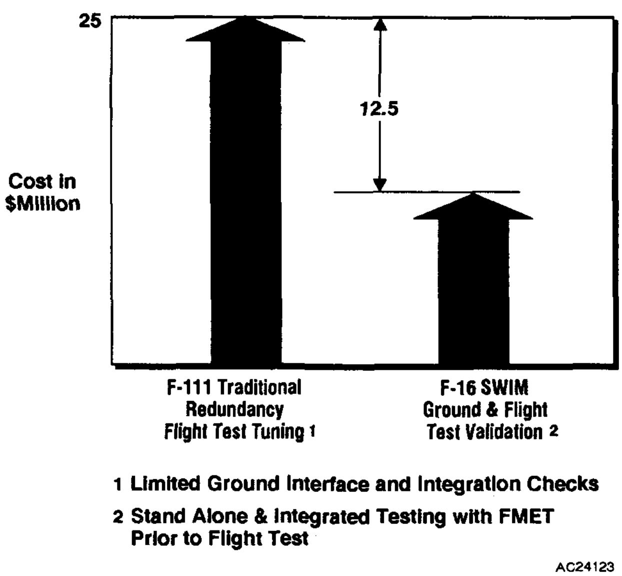


Figure 18 Cost Benefit Attributable to Validation of SWIM Features

Also, the SWIM validation process resulted in many changes to F-16 TF subsystems to resolve anomalies identified during the validation process. From FMET, potentially hazardous anomalies were identified and resolutions accomplished by SWIM feature mechanization changes of the auto-TF select monitors, cyclic TF command test, cyclic obstacle warn test, and data integrity monitors. Changes were also made to monitor logic, timing, comparison criteria, fault isolation, and cautions and warnings. These changes further enhanced F-16 TF safety, improved survivability (via false-alarm reduction), and increased robustness by enabling continued TF via compensation for more malfunctions than were possible prior to the validation process changes.

Conclusion

To achieve the predicted F-16 TF SWIM mishap-rate reduction with its phenomenal cost effectiveness advantage over traditional redundancy, SWIM features had to be validated to ensure dependable response to all hazardous malfunctions. To achieve maximum operational mission capability, a low false-alarm rate for the SWIM features had to be validated to guarantee prevention of excessive nuisance false-alarm recovery maneuvers that could degrade survivability as a result of increased-altitude exposure to surface-to-air weaponry.

The validation process, especially integrated system testing, provided the necessary data required to fine tune the SWIM mechanization. In the F-16 TF development, numerous improvements were made to the TF subsystems as a result of anomalies uncovered during the structured validation process. In particular, FMET led to the identification and resolution of some potentially hazardous anomalies involving SWIM feature mechanization. Changes were made as a result of the SWIM validation process that produced not only a safer F-16 TF system, but a more robust system than the initial F-16 TF system.

F-16 TF SWIM validation test results confirm that the SWIM features activate correctly with proper trip-level thresholds and persistence-count delays. This confirmation assures that the flight-critical F-16 TF system will operate with low mishap rates while maintaining survivability by avoiding excessive false-alarm fly-up maneuvers. Most notably, the SWIM validation process resulted in a tremendous cost savings because of the reduced number of test flights necessary to achieve certifiable SWIM feature operation as compared to a development program without such a validation approach.