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F-35 Mission Systems Design, Development, and Verification

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F-35 mission systems allow pilots to execute traditional advanced tactical missions critical to allied and partner nations. The systems include the most advanced sensor management and data fusion of any current fighter aircraft. These capabilities offer unmatched situational awareness to the pilot and provide decision aids that allow the pilot to make critical timely decisions. The development of these capabilities was accomplished utilizing use cases derived from mission vignettes to perform capability and model-based development. This approach was extended to the test and evaluation phase to develop mission-level scenarios used for validating the models and capabilities.

I. Introduction

THE F-35 comprises a set of highly common aircraft for the Air Force, Marine Corps, and Navy, as well as the 12 current F-35 partner nations. Although the airframes themselves possess slight differences unique to each variant's operating environment requirements, the mission systems' hardware and software are common. In addition, product-line engineering tags have been integrated into the mission systems' software requirements baseline. This enables repeatable and affordable country-unique builds for production off of a U.S. baseline.

The F-35 sensor suite includes the:

1) AN/APG-81 Active Electronically Scanned Array (AESA) radar,
2) AN/ASQ-239 Electronic Warfare (EW)/Countermeasures (CM) system,
3) AN/AAQ-40 Electro-Optical Targeting System (EOTS),
4) AN/AAQ-37 Electro-Optical (EO) Distributed Aperture System (DAS), and
5) AN/ASQ-242 Communications, Navigation, and Identification (CNI) avionics suite.

These five sensors provide F-35 fusion with object detection and measurements in the radio frequency (RF) and infrared (IR) spectrums. This compilation of data gathering disseminates more information about the environment than what has ever been available on a fighter aircraft.

In addition to receiving information from the onboard sensors, the F-35 receives off-board tracks and measurements from the Link 16 datalink and the Multifunction Advanced Data Link (MADL). Designed for 5th Generation aircraft, MADL provides fusion-quality data on all air and surface tracks to other members of the flight group. These data include the track state, track covariance, identification features, and passive RF data.

The amount and fidelity of the off-board information provided by MADL was one of the largest challenges for the fusion design. The capability of the sensors and information sharing across MADL presented a challenge for sensor fusion. The challenge was to ensure that the tracks displayed were real and not duplicated, which would result in display clutter. The last few software builds in the System Development and Demonstration (SDD) phase of the F-35 program were aimed at tackling display clutter problems. The objective was to ensure that the pilot had accurate and timely information to make real-time tactical decisions in the cockpit.

This paper discusses the design, development, and verification of each of these systems, as well as the system of systems integrated into the F-35 aircraft.

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II. The Vision

A. Aircraft Concept

The F-35 was born of the need for an affordable multirole, multi-service, multi-national (Air Force, Marine Corps, and Navy and international operators) fighter aircraft to replace an aging fleet of fighter and attack aircraft. The aircraft being replaced were battle tested by their operators. The challenge of this concept was rooted in the varied missions and operating environments that these platforms were satisfying. In order to replace their collective capabilities with a single fighter platform, a new way of thinking about single-seat fighter avionics design was needed.

The concept for the F-35 developed by Lockheed Martin centered on returning the pilot to the role of tactician. This principle was the driving force behind the avionics development plan. One of the Lockheed Martin Mission Systems team's design goals was to develop a set of sensors that could collect information across multiple spectrums. Another goal was to develop a sensor control scheme of autonomous sensor management. This, along with a next-generation cockpit, would provide the pilot with an unprecedented amount of information distilled down to an easily consumable format. Prior to this, the pilot spent precious minutes setting up radar scans and adjusting tilt, gain, and refresh rates, while also monitoring multiple displays to run an intercept. With this new suite, the pilot is able to view a picture of the multispectral battlespace in a consolidated format, as depicted in Fig. 1.

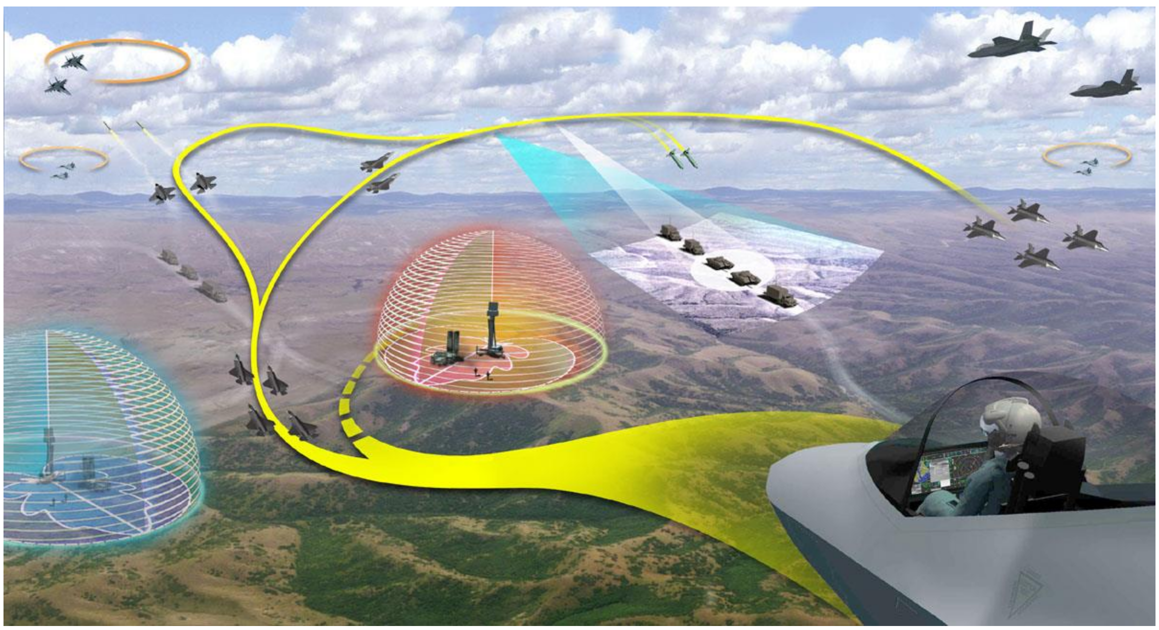


Fig. 1 Returning the pilot to the role of tactician.

The strategy for developing the avionics system was based upon a block buildup strategy. It was founded on basic warfighting capabilities and then built into the most advanced fighter weapons system currently in service. The most fundamental elements were developed first, and then the design moved to higher levels of capability. In this way, the team reduced the risk of software development produced by having a single large software release. This strategy was adapted from previous tactical fighter programs, such as the F-16, and more recently, the F-22. Those programs demonstrated that it is essential to break the software development into manageable blocks to reduce the complexity and cost of testing. Incremental releases also provide more of an opportunity to manage requirements creep and incorporate technology changes that directly benefit the warfighting capability. This was evident in the F-35 program's ability to implement additional weapons (e.g., GBU-39) and capabilities (e.g., operational test support changes) to support emerging requirements. The approach is structured as three development blocks that establish the basic flight control systems and essential mission systems before building up mission capability. The approach to building up the block plan in detail is depicted in **Error! Reference source not found.**.

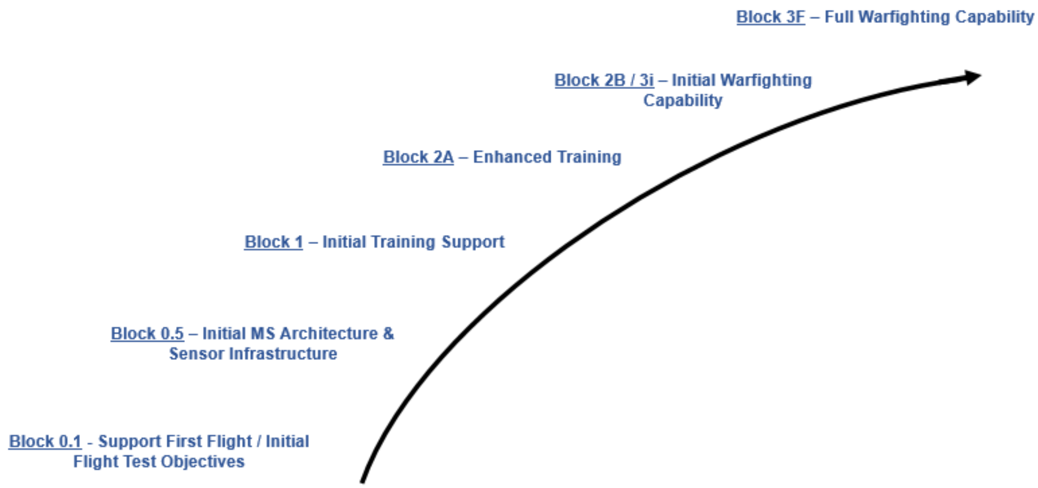


Fig. 2 Block development buildup.

B. System Architecture

It was recognized early in the concept development phase that the architecture of the mission systems would be key to the program's success. To succeed, many challenges had to be faced to develop the right architecture. One was that the computing resources needed for the full set of capabilities could not fit within the power, weight, volume, and thermal limitations of the air vehicle using available technology. Another was that the long development cycle and initial low-rate production was expected to result in diminishing manufacturing source (DMS) problems. In addition, the aircraft needed to be easily adaptable to support the unique needs of multiple countries. Further, it needed to be unclassified on the production line and on the ramp to avoid increased production and sustainment costs. Beyond this, it also needed to operate in future battlespaces where the movement of data at multiple levels would be key to interoperability.

The plan for overcoming computing resource and DMS challenges was to execute multiple technology refreshes of the computers during development. The processing update would allow Moore's law to take effect, providing increased processing capability over time that would fit within the limitations of the air vehicle. The updates would also allow updates to mitigate DMS and validate that the application software was independent of the underlying processor.

To achieve the goal of making the application software independent of the processor changes, three design approaches were used. The first approach (Fig. 3) was to layer the software on top of commercial, off-the-shelf (COTS) operating systems, under the assumption that the virtual platform would not change.

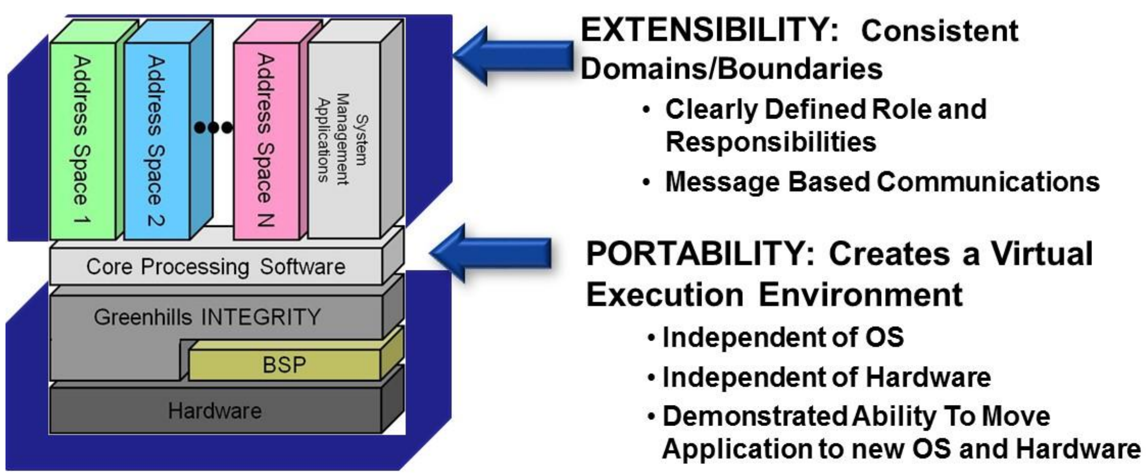


Fig. 3 Layered software design.

The second approach was to use rate-based processing for all threads when timing and latency were critical. This approach would achieve constant system-level timing, even with faster processing. Also, it would enable analyzing the system and proving that it was schedulable using rate-monotonic theory. Both benefits supported easier integration, reduced regression testing, and supported airworthiness and safety certification.

The third approach was to use messages for communication among all application software components, as well as components and subsystems [1]. This created controlled interfaces among the components and enabled moving applications to different processors without impacting the software. The approach contributed to solving interoperability and adapting the software for multiple countries. With the clearly defined interfaces and communication paths in the system, it was possible to control data paths using the trusted computing base. This enabled isolating data access for specific address spaces and ensured that the application remained at the designed security level for a specific datalink. Further, combining the messaging and access control with a COTS operating system with a high assurance level made it possible to design write-down applications for each datalink.

The capability was then advanced to interoperate with multiple participants in the battlespace at different operational levels and message formats. From this, the messaging and access control was partitioned to the external communications domain. This provided a broker for data on and off the aircraft, ensuring the correct classification level and translating the external data into formats consistent with internal data. It also transformed internal data into the message formats and needs of the external links.

III. F-35 Sensor Suite

The F-35 sensor suite includes the AN/APG-81 AESA radar, AN/ASQ-239 EW/CM system, AN/AAQ-40 EOTS, AN/AAQ-37 EO DAS, and AN/ASQ-242 CNI system. This collection of advanced multispectral sensors, shown in Fig. 4, provides the F-35 with a next-generation ability to see the battlespace.

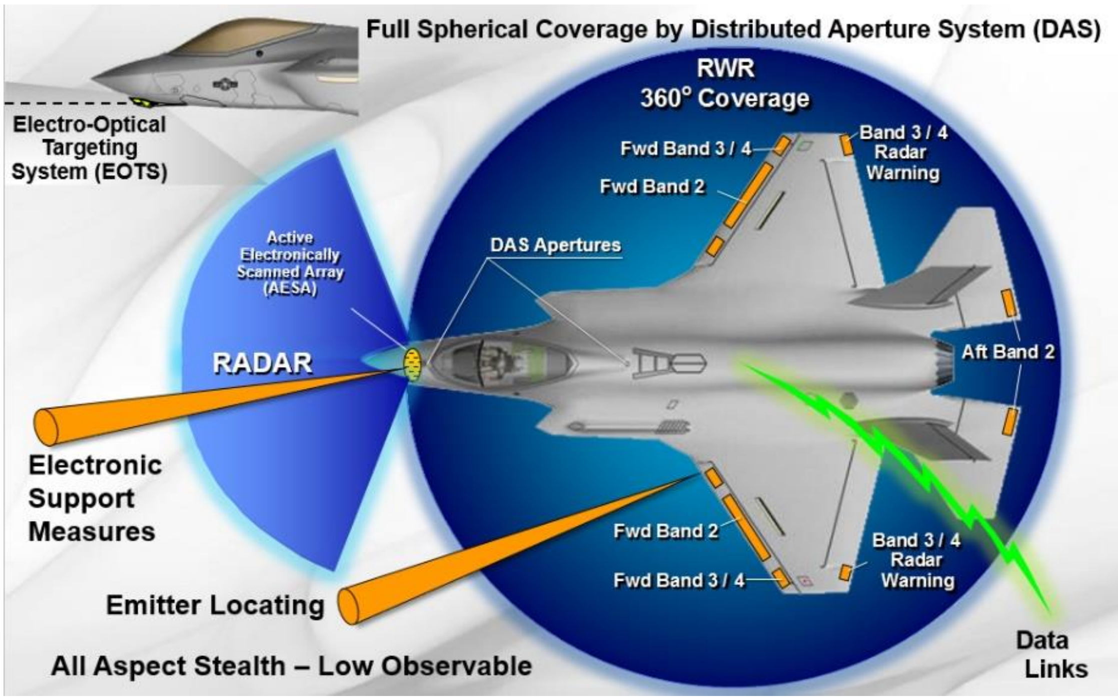


Fig. 4 F-35 installed sensor locations.

A. AN/APG-81 RADAR

Northrop Grumman's Electronic Systems sector's AN/APG-81 radar was developed as a next-generation version of its AN/APG-77 AESA radar, first fielded on the F-22A Raptor. The design was further refined with the AN/APG-80 fielded on the Block 60 F-16. This lineage of AESA radar designs allowed for a rapid development and insertion of previously fielded common waveforms in early software blocks. It also paved the way for more complex functions during later deliveries.

AN/APG-81 testing was approached in a buildup fashion of increasingly complex integration into the rest of the avionics system. The integration began with stand-alone laboratory testing isolated from the rest of the avionics system. It then progressed through the Northrup Grumman flying testbed, where dynamic stand-alone open-air testing was performed. From there the AN/APG-81 was integrated into the F-35 avionics suite to continue both laboratory testing and dynamic open-air testing on the Lockheed Martin Cooperative Avionics Test Bed (CATB). After the system was proven on the CATB it progressed to full airborne testing on the F-35. The buildup timeline for the AN/APG-81 is shown in Fig. 5.

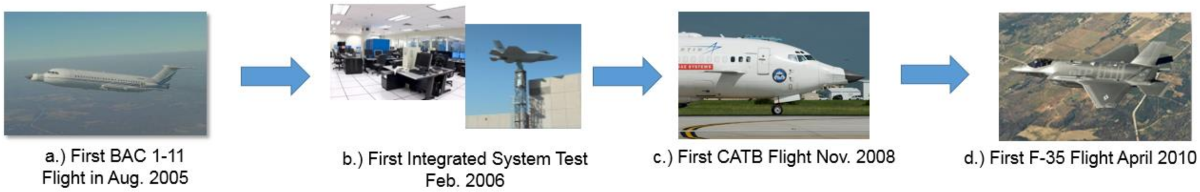


Fig. 5 AN/APG-81 integration buildup.

The F-35 radar system has an active, electronically scanned multifunction array (MFA) and the RF support electronics necessary to support a fully functional radar. It also has integrated radar software modes that are hosted on the integrated core processor. The radar operates through the nose radome, which has a wide bandwidth, enabling high-power transmissions over a large frequency range (**Error! Reference source not found.**).

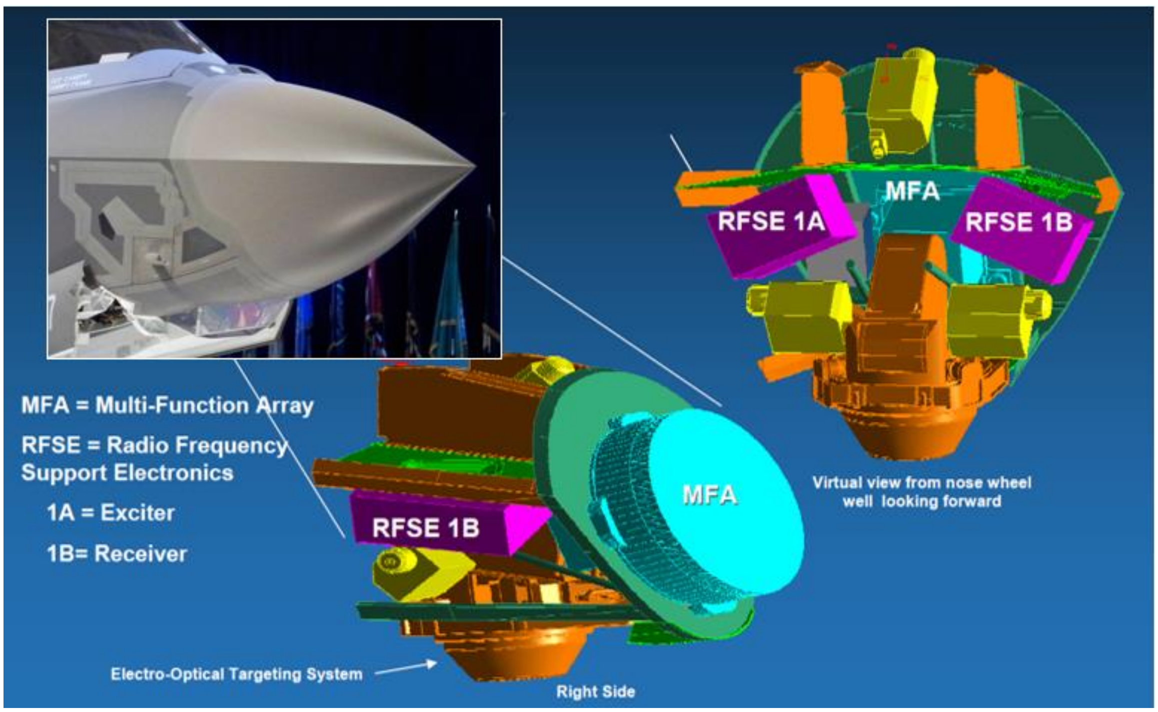


Fig. 6 Installed radome and radar locations.

The AN/APG-81 is designed to operate as a radar, electronics support measures (ESM) receiver, and jammer. It includes active and passive air-to-air (A/A) and air-to-surface (A/S) target detection, track, and identification capabilities. In addition, it allows many of these to be interleaved, providing both A/A and A/S functionality. The sensor also supports the Advanced Medium-Range Air-to-Air Missile (AMRAAM®) and synthetic aperture radar mapping, ground and sea moving target detection and track, and A/S ranging. Radar functions include electronic protection for operation in jamming environments and low probability of intercept features to minimize the likelihood of emissions being usefully detected by airborne or surface-based receivers. Radar functions also support system health determination and calibration. **Error! Reference source not found.** depicts the various radar functions.

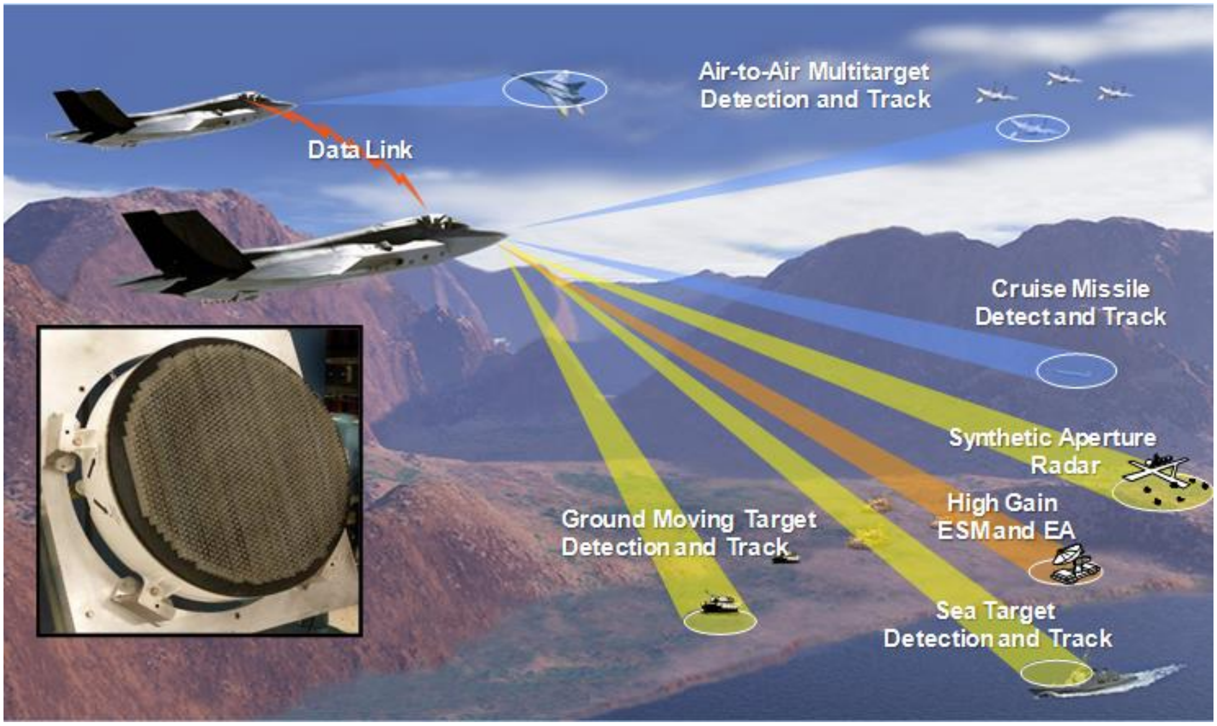


Fig. 7 Radar system air-to-air and air-to-surface operation.

B. AN/ASQ-239 Electronic Warfare/Countermeasure System

The AN/ASQ-239 EW/CM system is an integrated suite of hardware and software. It is optimized and designed to provide the F-35 with a high level of A/A and A/S threat detection and self-protection. It can search, detect, identify, locate, and counter RF and IR threats. The EW system supports the application of electronic support measures (ESM) through such functions as:

1) radar warning,
2) emitter geolocation,
3) multi-ship emitter location (including high-sensitivity states),
4) high-gain (HG) ESM,
5) HG electronic CM, and
6) HG electronic attack (EA) via radar MFA utilization.

The EW functions are designed for:

1) wide frequency coverage,
2) quick reaction time,
3) high sensitivity and probability of intercept,
4) accurate direction finding and emitter geolocation,
5) multi-ship geolocation, and
6) self-protection countermeasures and jamming.

The countermeasure subsystem provides multiple self-defense responses, including pre-emptive and reactive techniques, based on available expendable payload and/or threat-specific self-protection plans. The EW/CM system provides emitter tracks to the sensor fusion function, which fuses EW track reports and other sensors (e.g., radar and DAS, off-board sensors) and displays the information to the pilot. The EW/CM system consists of the following primary elements:

1) Band 3/4 apertures,
2) Band 3/4 aperture electronics,
3) centralized EW electronics (Racks 2A and 2B),
4) CM controller unit,
5) CM dispensers,
6) RF and digital interfaces with the MFA, and
7) digital-clock reference interfaces with the CNI system.

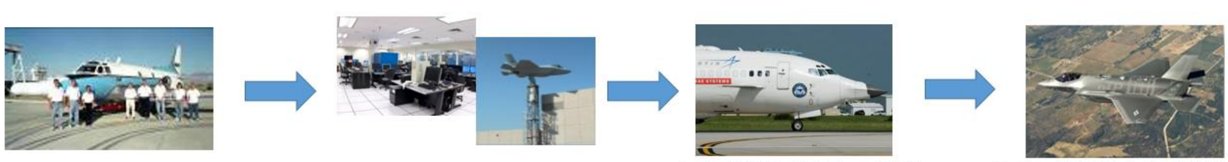
The installation locations of the EW/CM system-related equipment are depicted in **Error! Reference source not found.**. The EW system is common among the three F-35 variants, except for the forward Band 3/4 arrays, which employ longer elements for the F-35C Carrier Variant (CV). Also differing, the distance between the inboard and outboard arrays is less on the CV variant due to the wing fold. In addition to the EW Band 3/4 apertures, the radar MFA is employed to support EW functions. There are growth provisions allocated for Band 5 radar warning such that Band 5 apertures, aperture electronics, and the Band 5 switch can be incorporated into the EW subsystem architecture.

Fig. 8 EW equipment location.

The EW apertures comprise six multi-element antenna array sets covering portions of the Band 3 and Band 4 frequency spectrum, along with both vertical and horizontal polarization. All the arrays have azimuth (AZ)-only designs that do not rely on the use of elevation (EL) arrays. The passive array assemblies use a traveling wave-notch element approach designed to balance gain, polarization, field of view (FOV), and radar cross-section features. Each Band 3/4 aperture feeds an aperture electronics module that amplifies and passes the detected RF signals from the apertures. It does this through a switch matrix and tuners that distribute the RF to a set of wideband EW receivers (EWRs). The switch matrix also receives RF signals from the radar MFA when tasked to support HG modes.

The EWR suite consists of 12 wideband receivers grouped into three integrated sets of four channel receivers. The wideband receivers take in RF energy and convert the data into digital information via a set of high-speed analog-to-digital converters for processing. Each EWR performs initial data processing and generates pulse parameter reports that are sent to the EW controller/preprocessor. The processor then provides further signal processing and algorithms to support all EW activities. Various intelligence products combine to produce an electronic intelligence (ELINT) database in a preplanned mission data file. This data file provides the system with the necessary parametric descriptions of the emitters of interest for emitter identification and scan schedule operations.

EW system testing was performed in a buildup fashion of increasingly complex integration into the rest of the avionics system. The integration began with stand-alone laboratory testing isolated from the rest of the avionics system and progressed through a Sabreliner T-39-based flying testbed. From there the EW system was integrated into the F-35 avionics suite to continue both laboratory testing and dynamic open-air testing on the Lockheed Martin CATB. After the system was proven on the CATB it progressed to full airborne testing on the F-35. The buildup timeline for the EW system is shown in Fig. 5.



a.) First T-39 Flight June 2005 b.) First Integrated System Test May 2006 c.) First CATB Flight Aug. 2007 d.) First F-35 Flight April 2010

Fig. 9 Electronic warfare system integration buildup.

C. AN/AAQ-40 Electro-Optical Targeting System

The F-35 requirement for a low observable (LO) combat configuration did not allow for the traditional targeting forward-looking infrared (TFLIR) solution. The legacy pod systems could not be both missionized and easily concealed for LO operations. The solution was to integrate the targeting pod system into the outer mold line of the aircraft. The EOTS, built by Lockheed Martin Missiles and Fire Control, was built specifically for the F-35 to provide the jet with an LO IR targeting capability. Its integration was approached in a buildup fashion, as shown in Fig. 10. The initial open-air testing was performed with a modified Sabreliner T-39 jet to test the EOTS as a stand-alone sensor to verify sensor-level behavior. The EOTS was integrated into the rest of the avionics system on the Lockheed Martin CATB flying testbed to test the interactions between the sensor and the full avionics system with a pilot in the loop. The final testing and verification came with the full integration of the EOTS into the F-35.

Fig. 10 EOTS integration buildup.

The EOTS is an internally mounted advanced mid-wave infrared (MWIR) targeting system with a faceted window having LO characteristics, designed for A/A and A/S targeting support. By using the mid-wave portion of the IR spectrum the EOTS provides a sharper image and less susceptibility to target obscuration from smoke and haze. The EOTS may be used in the imaging mode in A/A and A/S, or in the IR search and track (IRST) mode in A/A. Design consideration has been given to achieving:

1) a good receiver signal-to-noise ratio,
2) effective FOVs for A/A and A/S performance,
3) a broad field of regard,
4) auto-search pattern modes, and
5) low false alarm rates.

The EOTS's functionality consists of a TFLIR image, laser range finder/designator, laser spot tracker, and IRST, as shown in Fig. 11. The EOTS uses low-profile gimbals with an optical system that maintains boresight accuracy between the forward-looking infrared (FLIR) and laser functions. Precise stabilization of the EOTS's line of sight is achieved by gyro-controlled AZ and EL gimbals, and fine stabilization is achieved through a fast-steering mirror. Equipped with a staring 1024-by-1024-element MWIR focal plane array, the EOTS is a dual-FOV system. The narrow FOV is optimized for targeting functions, and the wide FOV is developed to maximize search performance.

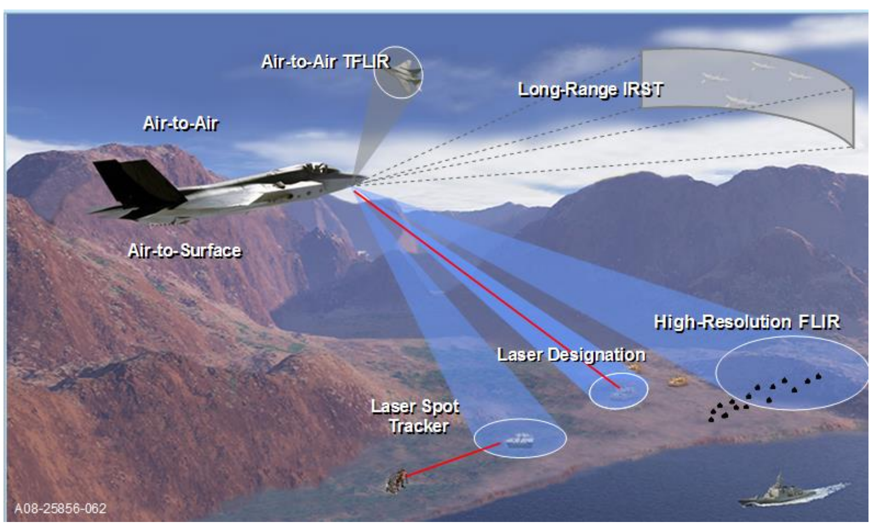


Fig. 11 EOTS capabilities.

D. AN/AAQ-37 Electro-Optical Distributed Aperture System

The program required a 360-degree spherical coverage missile warning system. The EO DAS consists of six identical MWIR sensors distributed on the aircraft, each with a corresponding airframe window panel. The sensors are installed such that their respective FOVs (95-degree AZ and EL) overlap to provide total spherical coverage. This EO DAS subsystem provides the pilot with both an MWIR tracking capability and FLIR visual scene, but its FLIR is more comprehensive. In legacy FLIR systems the pilot's visual scene was limited to the forward sector. With the F-35's EO DAS, the pilot has a 360-degree spherical view of the environment. This allows for a true synthetic vision system, with the image displayed on the pilot's helmet-mounted display (HMD).

The EO DAS integration began with a single sensor installation within a pod. This pod was mounted on an F-16 to support initial testing and data collection for image processing algorithm validation. This podded system was also mounted on a QF-4 drone to enable testing of the missile warning function. The next step in integration was to mount a sensor in an integration-representative fashion on the Northrop Grumman-owned BAC 1-11 flying testbed. The first introduction of multiple EO DAS cameras into the integrated avionics system was performed on the Lockheed Martin CATB platform. This marked the beginning of integrating the EO DAS sensors into the Lockheed Martin-developed fusion algorithms. The final step to fully incorporate the EO DAS into the integrated avionics system came in March 2011, with the first flight testing on an F-35. The EO DAS integration timeline is depicted in Fig. 12.

Fig. 12 DAS buildup integration.

Key EO DAS operational functions in Block 1 of Flight Test Update B are navigation forward-looking infrared (NAVFLIR) and missile warning. Block 2 of Flight Test Update B added surface-to-air missile (SAM) launch point reporting and situational awareness IRST. These EO DAS functions are available simultaneously and serve to enhance situational awareness and defensive response. Figure 13 illustrates these capabilities.

Fig. 13 DAS capabilities.

E. AN/ASQ-242 Communications, Navigation, and Identification System

The CNI system (Fig. 14) is an integrated subsystem designed to provide a broad spectrum of:

1) secure/anti-jam/covert voice and data communications,
2) precise radio navigation and landing capability,
3) self-identification, beyond-visual-range target identification, and
4) connectivity with off-board sources of information.

In support of the stealthy operation and design goals of the F-35, the CNI subsystem includes techniques to reduce the probability of detection, interception, and exploitation, and can deploy electronic CM. These techniques include frequency agility, spread spectrum, emission control, antenna directivity, and low probability of intercept design capabilities. The CNI system provides interoperability with existing (legacy) military and civilian communication, RF navigation, and Identification Friend Foe (IFF)/surveillance systems. It is also interoperable with appropriate civilian systems for U.S. and European airspace operations. The CNI system provides an inherent growth capability and the flexibility to incorporate additional functionality through software upgrades. It also provides for hardware upgrades driven by parts obsolescence and enables manufacturing cost reduction and/or performance improvement.

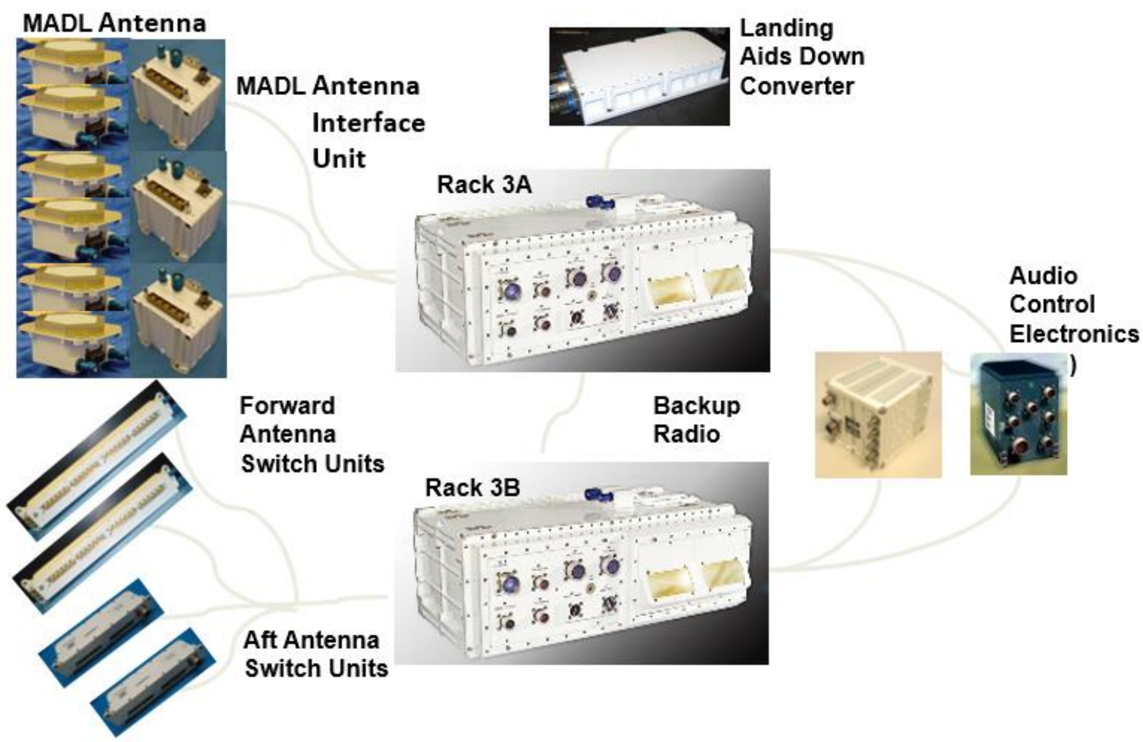


Fig. 14 CNI system components.

The CNI-specific data, signal, and cryptographic processing are performed in unique CNI processors and the integrated core processor as required. The CNI system includes all functionality related to audio generation and distribution for the aircraft. This includes the pilot intercom; integrated caution, advisory, and warning messaging; pilot audio alerts; and support for the voice recognition function.

The CNI system includes an all-attitude inertial navigation system (INS) and anti-jam GPS. These provide outputs of linear and angular acceleration, velocity, body angular rates, position, attitude (roll, pitch, and platform AZ), magnetic and true heading, altitude, time tags, and time. The INS and GPS provide navigation data to the ownship kinematic model, which produces the navigation solution for the aircraft. The baseline system provides high-rate motion compensation data to the radar and EOTS.

IV. Fusing the Data into Information

The F-35 fusion engine is the software module at the heart of the integrated mission systems capability on the aircraft. Fusion involves constructing an integrated description and interpretation of the tactical situation surrounding ownship [2]. It draws from onboard, cooperative, and off-board data sources to enhance situational awareness, lethality, and survivability [2]. The fusion functionality is divided into two major sub-functions: air target management (ATM) and surface target management (STM). The purposes of these functions are to optimize the quality of air and surface target information, respectively. Their functionality is implemented in three primarily software modules: the A/A tactical situation model (AATSM), the A/S tactical situation model (ASTSM), and the sensor schedule (SS).

The AATSM software module receives data from onboard and off-board sources about air objects in the environment. It then integrates this information into kinematic and identification estimates for each air object. Similarly, the ASTSM software module receives data from onboard and off-board sources about surface objects in the environment. It then integrates this information into kinematic and identification estimates for each surface object.

Objects that are ambiguous between air and surface are sent to both tactical situation models (TSMs). Each TSM assesses the quality of its tracks to identify any information needs. The system track information needs (STINs) are sent from the TSMs to the SS software module. The SS prioritizes the information needs by track and selects the appropriate sensor mode command to issue in order to satisfy the information need. The SS provides the autonomous control of the tactical sensors to balance the track information need and the background volume search needs.

Measurement and track data is sent to fusion from the onboard sensors (e.g., radar, EW, CNI, EOTS, DAS) and off-boards sources (e.g., MADL, Link 16). When this information is received at the TSM, the data enter the data association process. This process determines whether the new data constitute an update for an existing system (fusion) track or potentially new tracks. After being associated with a new or existing track, data are sent to the state estimation to update the kinematic, identification, and rules of engagement (ROE) states of the object.

Kinematic estimation refers to the position and velocity estimate of an object. It can also include an acceleration estimate for maneuvering air track. The kinematic estimate also includes the covariance for the track, an estimate of the track accuracy. Identification estimation provides an estimate and confidence of the affiliation, class, and type (platform) of the object. The identification process also evaluates the pilot-programmable ROE assistant rule to determine when the sensing states and confidences have been met for declaration. Estimation publishes the updated track state (kinematic, identification, and ROE statuses) to the system track file. At a periodic rate (about once a second), each track is prioritized and then evaluated to determine whether the kinematic and identification content meets the required accuracy and completeness. Any shortfall for a given track becomes STINs. The STIN message for the air and surface tracks are sent to the SS to make future tasking decisions for the onboard sensor resource. The process continues in a closed-loop fashion with new pieces of data from the sensors or datalinks. Figure 15 illustrates this process.

The results of this fusion of information are provided to the other elements in mission systems. They are provided to the pilot/vehicle interface (PVI) for display, fire control and stores for weapon support, and EW for CM support. This allows these elements to perform their related mission functions to provide:

1) a clearer tactical picture,
2) improved spatial and temporal coverage,
3) improved kinematic accuracy and identification confidence, and
4) enhanced operational robustness.

For a clearer tactical picture, multiple detections of an entity are combined into a single track instead of multiple tracks. For improved spatial and temporal coverage, a target can be continuously tracked across multiple sensors and FOVs. This is made possible by the extended spatial and temporal coverage of the onboard sensors, as well as the off-board contributor. Improved kinematic accuracy and identification confidence requires the effective integration of independent measurements of the track from multiple sensors or aircraft. This integration is what improves the detection, tracking, positional accuracy, and identification confidence. Enhanced operational robustness requires the abilities to fuse observations from different sensors and hand off targets between sensors. This leads to increased track resilience to sensor outages or countermeasures. Increased dimensionality of the measurement space (i.e., different sensors measuring various portions of the electromagnetic spectrum) then reduces vulnerability to denial of any single portion of the measurement space.

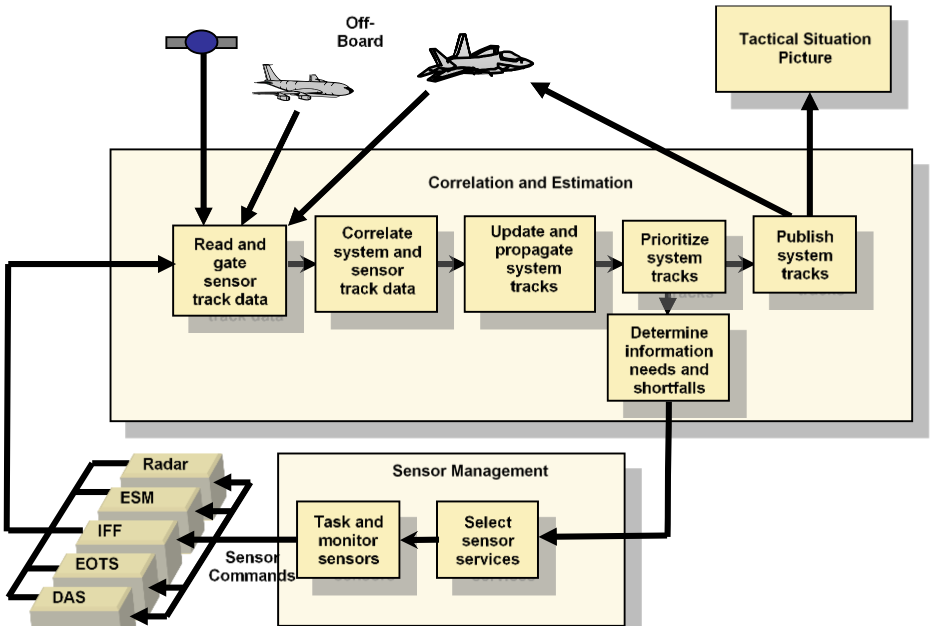


Fig. 15 Closed-loop sensor data fusion.

V. Next-Generation Cockpit

The visible product of this information gathering is ultimately the fighter pilot's office. The F-35 cockpit (Fig. 16) was designed to accommodate the unprecedented amount of data available to the pilot of a single-seat fighter. The F-35 display suite and associated PVI were conceptualized through a multi-year immersive simulation and evaluation, along with flight demonstrations on surrogate aircraft.

Fig. 16 F-35 cockpit.

A. Helmet-Mounted Display

The HMD, included in Fig. 17, was developed to provide the pilot with both existing and evolutionary tactical advantages. In it, legacy systems, such as the joint helmet-mounted cueing system (JHMCS), were supplemented by an integrated digital night vision camera (NVC). The HMD also provides integrated flight reference information that allowed for the removal of the traditional head-up display (HUD). This improved upon the legacy tactical and navigation display, with an integration surpassing that of the HUD/JHMCS combination. The HMD design evolved from concepts demonstrated using the Viper-II HMD on the Variable-stability In-flight Simulator Test Aircraft (VISTA) F-16 program. This was the basis for proving the concept of a HUD-less cockpit. The HMD design and integration then matured through several iterations during the SDD phase. Ultimately, it met ejection safety limits (Gen I to Gen II), program requirements for line-of-sight accuracy (Gen II to Gen III), and (later) full ejection envelope (Gen III to Gen III Lite).

The HMD is a monochromatic 1280-by-1024-resolution bi-ocular display with a 30-by-40-degree FOV. The helmet position is determined by a hybrid (magnetic, inertial, and optical) tracker system that allows for low-latency symbol positioning. The HMD can display either the MWIR image provided by the DAS or a near-IR image provided by the embedded NVC. When the pilot is looking forward, the NVC image is blended with the image provided by a fixed camera mounted on the glare shield. This is done to eliminate the obstruction caused by the canopy bow frame.

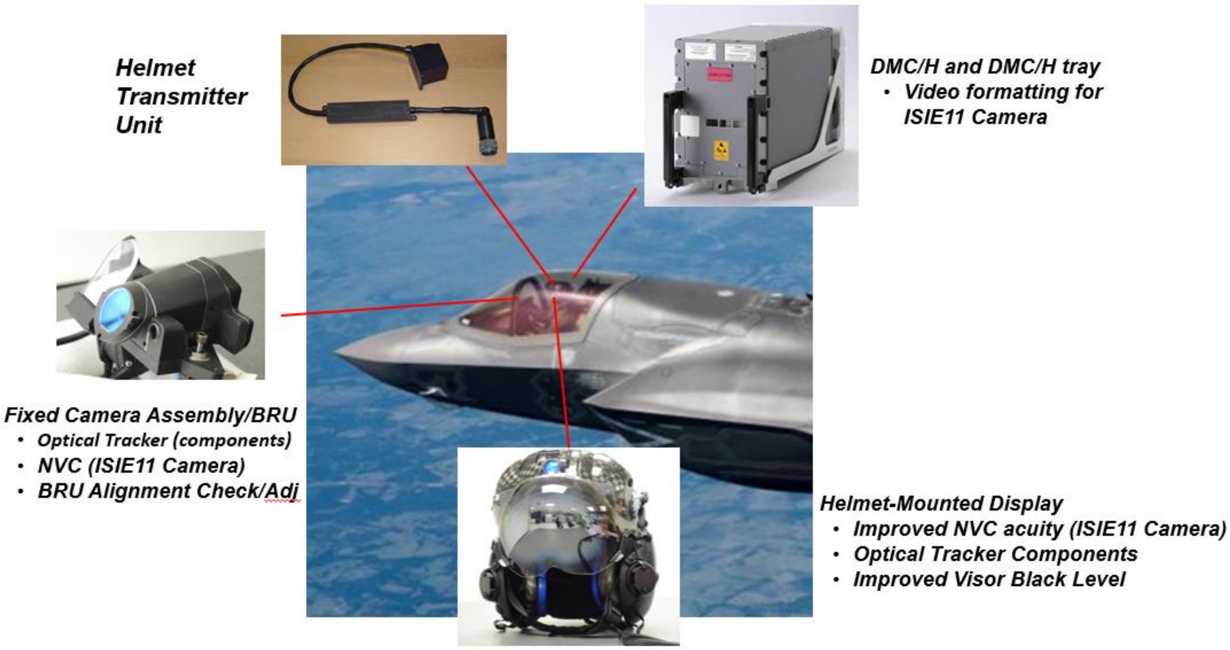


Fig. 17 Gen III helmet-mounted display system.

B. Panoramic Cockpit Display

A striking difference between the F-35 and other legacy fighters is the incorporation of a large-format touchscreen display. The panoramic cockpit display (PCD) provides the pilot with a programmable and reconfigurable display that allows for customized views to satisfy mission needs. The PCD was the replacement selected for the original rear-projection multifunction display suite (MFDS) [3]. The MFDS rear-projection display technology was abandoned due to several factors. The lack of available contrast and insufficient resolution for tactical displays within the F-35 cockpit environment caused the symbols to be difficult to read. Pilots required the system to be at full brightness for all daytime flights, which shortened the projection lamp lifespan. This resulted in frequent maintenance being needed for the developmental test aircraft. Due to these and other factors, the program chose to recompete the display and associated processing elements early in the SDD contract.

The PCD consists of an 8-by-20 active matrix liquid crystal display and an electronics unit (EU), as shown in Fig. 18. The display resolution is 2560-by-1024 color pixels. The PCD uses a portal window concept to support multiple formats on a single display surface. A touchscreen interface and/or hands-on throttle and stick provides pilot input to the PCD. The EU has two separate power supplies and independent display management computers for each half (left and right) of the display. This, along with the ability to display any format on either display, provides redundancy to support mission operations and airworthiness. The EU accepts multiple video inputs for display on the PCD and is also responsible for outputting an MPEG-2 standard compressed video stream to a recording function to facilitate pilot debrief. The PCD unit is compatible with the night vision imagery system.

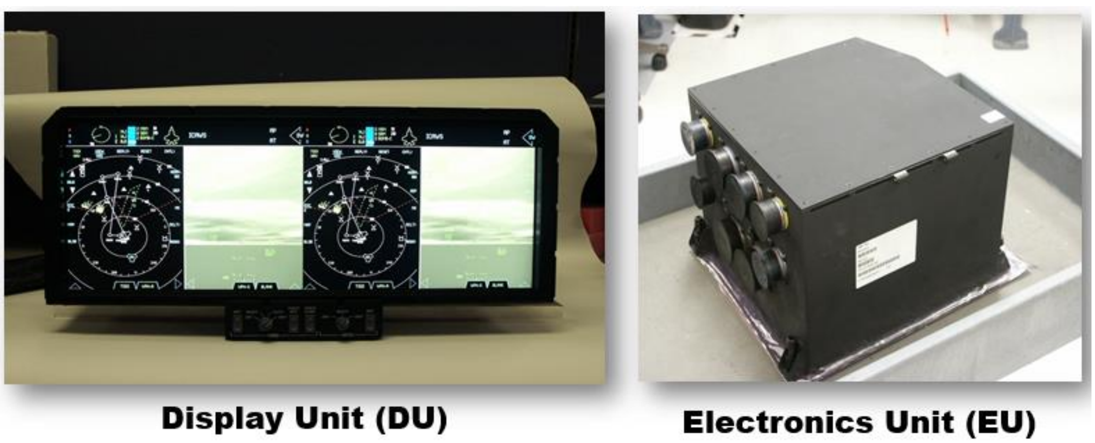


Fig. 18 PCD display unit and electronics unit.

VI. Verification

A challenge for the F-35 program was to reduce the cost of integration and verification. The concept developed was based upon verification of performance to specific missions depicted in Fig. 19. The focus of the plan was to break down the missions into verifiable pieces that could be developed into a buildup plan for test and verification. This allowed a view of the problem space that did not center on any one specific scenario. Instead, it took a broader look at how the aircraft performed in representative test scenarios.

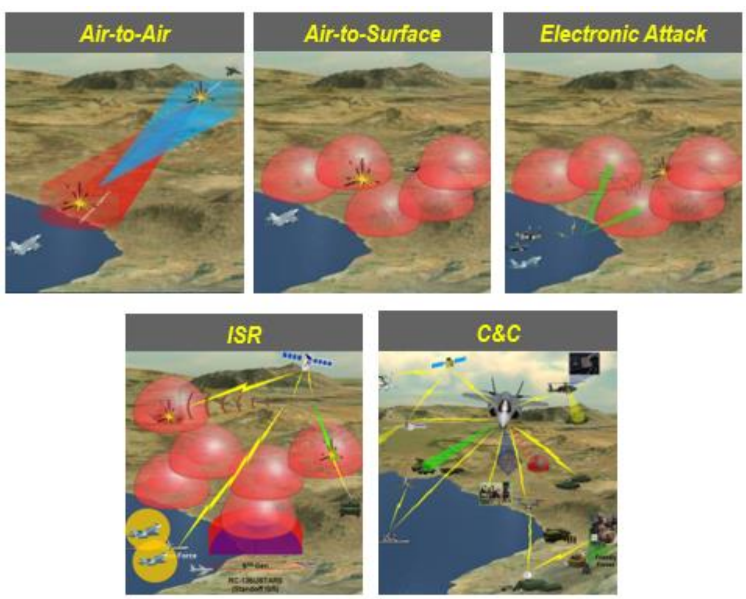


Fig. 19 F-35 mission types.

To rely less on flight testing for developmental buildup, the F-35 Mission Systems team leveraged mission-representative vignettes that had been developed for verification. The team applied those same scenarios and criteria to the lower-level testing. The subsystem and laboratory testing venues allowed for a rapid turn of changes once a testable product was provided. The laboratories constructed, along with their associated capabilities listed in Table 1, provided unique venues to add or subtract levels of complexity to grow the system and isolate issues.

Table 1 Verification laboratories.

Laboratories	Capabilities
Simulated Systems Integration Station	1) Core avionics hardware and PVI 2) Supplier-provided models for sensors and weapons 3) Ability to connect to vehicle system and other integrated avionics laboratories
Open-Air Systems Integration Station	1) Open-air environment with representative apertures and associated hardware 2) Full avionics hardware suite 3) Capable of CATB cooperative testing
Stimulator-based Systems Integration Station	1) RF and IR stimulation capability 2) Representative sensor hardware minus apertures 3) Multi-aircraft cooperative simulation utilizing using connections to multiple laboratories

The F-35 Mission Systems team used mission-based scenarios and a pyramid-type test approach (Fig. **20**). With these, the team could progressively add complexity to the integrated system and quickly compare system performance to uncover problems early in integration. This also allowed for releases to flight test that may have a limitation in one area but verification-capable performance in another. By including the developmental test pilots in the final laboratory testing sessions, pilots were able to get an idea of performance and learn where they may experience shortfalls. This allowed them to more efficiently perform flight tests to gather the required data. The partnership and communication between the developmental test pilots and the development team proved essential to maintaining the rapid pace required to achieve full system verification.

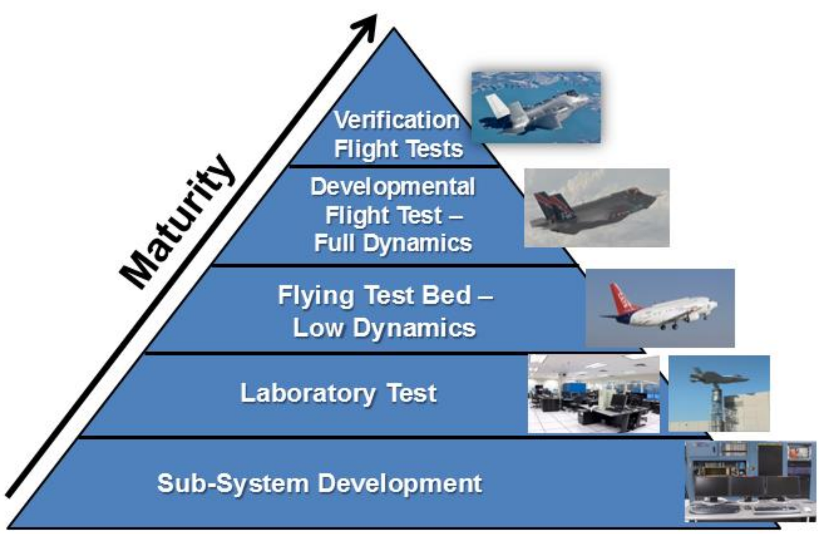


Fig. 20 **Test buildup methodology.**

VII. Conclusion

The F-35 mission systems suite of sensors, displays, and advanced fusion algorithms was developed to satisfy the need to provide tomorrow's fighter pilot with an unprecedented level of information. At the same time, the suite allows pilots to still perform the tactics mandated by the mission. The F-35's performance has been demonstrated in more than 100,000 flight hours covering developmental test, operational test buildup, and training flights. The F-35 also showcased its capability during Red Flag 17-1, where the platform achieved a 20:1 kill ratio in simulated combat exercises [4].

F-35 mission systems design, development, and verification was achieved with an object-oriented, multi-level COTS-based architecture and a suite of powerful multi-spectral sensors. As successful products of the F-35 Mission Systems team's efforts, the advanced fusion algorithms and next-generation cockpit enable the pilot to return to the role of tactician.

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