Visionary Systems

All three variants of the F-35 Lightning II are equipped with the same suite of mission systems. By applying cutting edge technology, the systems are not just complex but designed to provide a picture of the battle space that is better than any fighter pilot has ever had before. Using the AAQ-40 Electro-Optical Targeting System and the AAQ-37 Distributed Aperture System, the F-35 pilot is fed information on the Panoramic Cockpit Display and on the visor of his Helmet-Mounted Display.

AAQ-40 Electro-Optical Targeting System (EOTS)

With ample experience in building some of the world's most advanced targeting systems, scientists and engineers working for Lockheed Martin's Missiles and Fire Control in Orlando, Florida, were in a good position to take targeting capability even further when the requirements for the F-35 were received. The resulting AN/AAQ-40 Electro-Optical Targeting System (EOTS) leverages on the experience gained from producing the LANTIRN targeting system ('the genesis of night, precision weapons employment'), the AN/AAQ-33 Sniper advanced targeting pod, and the AN/AAS-42 infrared search and track (IRST) system used on the F-14D Super Tomcat. "The EOTS is the first sensor to combine a targeting FLIR and IRST. Marrying the two capabilities into one sensor was the big technical challenge in developing the system," said Don Bolling, Lockheed Martin's Business Development Manager for EOTS.

Principally viewed as an air-to-ground targeting pod, the EOTS was initially destined for every third F-35 produced. But the US Navy successfully argued for EOTS to be fitted to every F-35 built citing the capability as an absolute indispensible part of the sensor suite used throughout the mission spectrum. The EOTS provides laser designation, laser spot tracker for cooperative engagements, air-to-air and air-to-ground tracking FLIR, digital zoom, wide area IRST and generation of geo-coordinate to support GPS-guided weapons. All three variants of the F-35 are fitted with the EOTS.

Measuring (W x D x H) approximately 19.4 x 27.5 x 32.1 inches (493 x 698 x 815mm), the EOTS populates a box with a volume of less than 4cu ft and weighs 202lb (91kg). "There are DAS sensors on the left and the right of EOTS, and radar equipment above, the space constraints are very tight," said Bolling. By comparison a Sniper pod comprises a 7ft 6in (2.3m) long tube weighing about 440lb (200kg). One reason for the difference in size between the Sniper pod and the EOTS is the cooling method used. Most conventional targeting pods such as Sniper are air-cooled requiring the necessary system to be carried on the back of the pod. The EOTS is a liquid-cooled system using PAO (polyalphaolefin) fed from the aircraft.

The EOTS is positioned within the F-35 lower forward fuselage between the radar and cockpit bulkheads. "When you think of the level of complexity in a targeting system, which are like telescopes with long straight optical paths, and see where the EOTS is positioned on the F-35, space is at a premium," said the EOTS boss.

Space is limited to such an extent that a standard targeting system with a straight optical path is physically impossible to house in the space available. The EOTS optical path is therefore folded via mirrors and prisms to refract the light off several different surfaces to direct it on to the focal plane array and fit within the space. "The system is a compact optical device that uses multiple wavebands," said Casey Contini, director of F-35 electro-optics and helmet systems at Lockheed Martin.

"We are effectively bending light at least four times from the point where it enters the window and is finally directed onto the focal plane array or the detector, which was a significant challenge," Don Bolling extolled.

"What makes the F-35 truly magic is that for the first time you have a fused sensor suite. The APG-81 radar is much more accurate in range presentation against an airborne target than an IR system can be, and the EOTS is much more accurate in azimuth down to a single pixel than radar can be. Combine the two capabilities together and you get a much smaller target location uncertainty, which means your weapons effect will be greater and if required your designation accuracy to cue somebody else to that spot will be much tighter. You are able to share the capabilities of each of the sensors and reduce uncertainty," he said.

The EOTS sits behind a faceted window assembly comprising seven sapphire panels. A panel refers to an individual part that fits into a frame and is secured in place to comprise the whole window assembly. Driven by the requirement to comply with the aircraft's radar signature, the EOTS window assembly is the first such design in existence. By comparison, Lockheed Martin's AAQ-33 Sniper pod has four smaller panels with a much shallower angle of incidence between the sensor and the window. Maintaining the required optical performance and complying with radar signature requirements presented a real challenge according to Bolling.

Internally the EOTS has unique designs for the gimbal and the main entry lens called the A-focal or azimuth assembly which provides the horizon-to-horizon view. It is positioned right up against the window with about a 1/4 inch (6mm) of sway space. This intricate design was driven by the requirement for multiple fields of view with a digital zoom in a low-observable application.

A second lens known as the elevation assembly is an innovatively designed mirror that sits opposite and at a 45° angle to the main A-focal and rotates to provide vertical

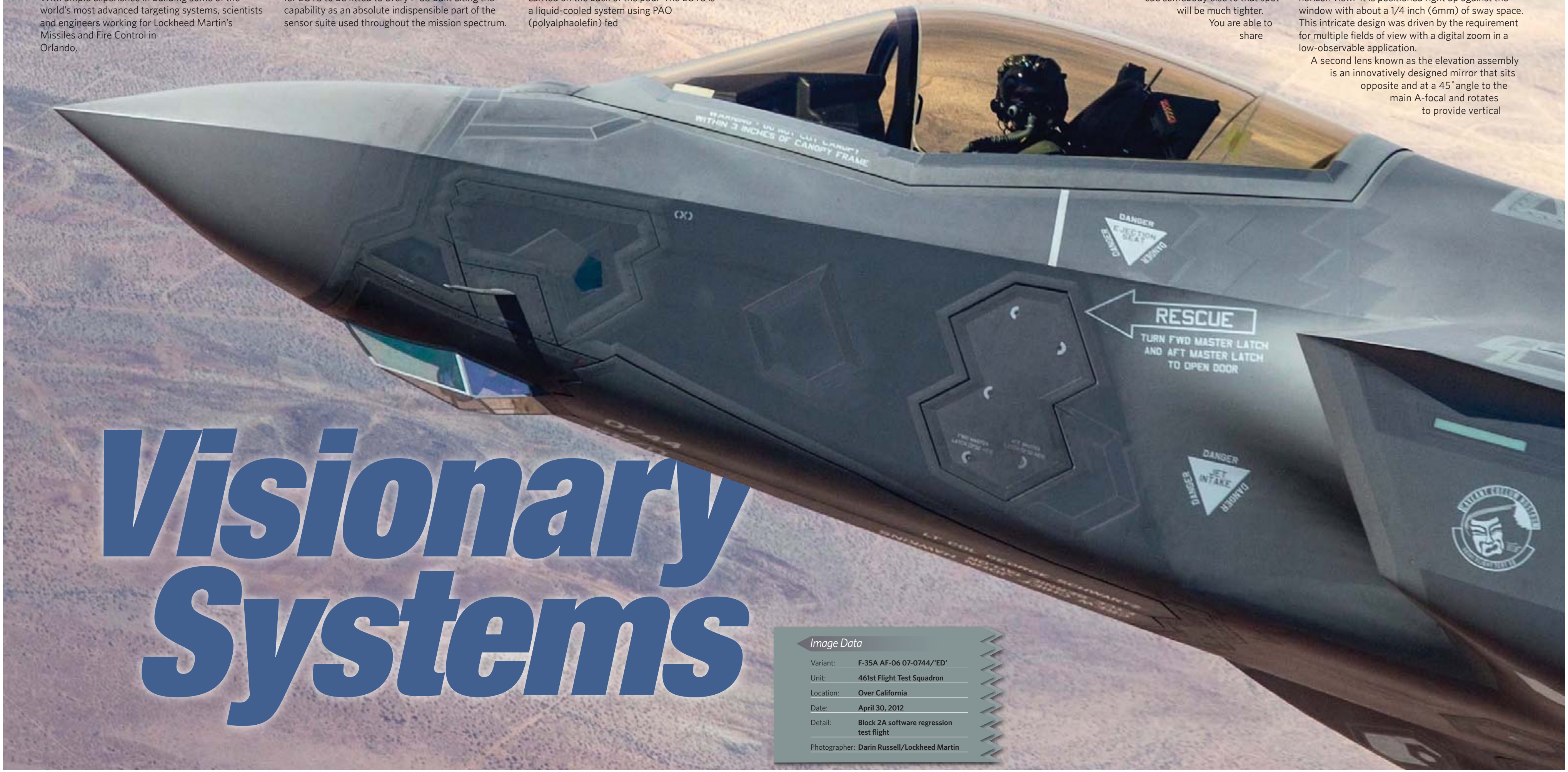


Image Data

Variant:	F-35A AF-06 07-0744/'ED'
Unit:	461st Flight Test Squadron
Location:	Over California
Date:	April 30, 2012
Detail:	Block 2A software regression test flight
Photographer:	Darin Russell/Lockheed Martin

System: **AN/AAQ-40 Electro-Optical Targeting System** Detail: **The sapphire colour of the panels is shown to good effect in this side shot of the EOTS faceted window** Photograph: **Lockheed Martin**

System: **AN/AAQ-40 Electro-Optical Targeting System** Detail: **The EOTS measures approximately 19.4 x 27.5 x 32.1 inches, weighs 202lb and populates a box with a volume of less than 4 cu ft.** Photograph: **Lockheed Martin**

System: **AN/AAQ-40 Electro-Optical Targeting System** Detail: **The aft end of the faceted window assembly showing three of the seven sapphire panels** Photograph: **Lockheed Martin**

System: **AN/AAQ-40 Electro-Optical Targeting System** Detail: **The faceted window of the EOTS on an F-35A assigned to the 58th Fighter Squadron based at Eglin Air Force Base, Florida** Photographer: **Jim Haseltine**

coverage. The elevation assembly directs the light into the optical path.

At the top of the system is the laser, the same type of laser used in the Sniper ATP but with a different output path. Just below the laser on top of the gimbal assembly are two circuit boards or electronic control assemblies. One provides control to the power servo and the other is an image processor mechanism. A fibre-optic channel feeds data from the sensor directly to the integrated core processor.

The entire EOTS assembly has a composite shroud to provide cover from debris and act as a structural element that assists with stabilising the system. System stabilisation is hugely important for holding a spot on the ground and very steady so a geo coordinate can be derived and fed to a GPS-guided weapon for targeting.

Each time the EOTS powers up, an automatic boresight aligns the laser and the FLIR. The boresight mechanism is a module fitted on the back of the gimbal. At power-up the sensor slews into the boresight module and aligns itself with the FLIR and the laser so that they are pointing at the same spot. Having a single aperture means the FLIR and the laser all go through the same optical path.

"All of the sensors on the aircraft need to be boresighted to a spot in space so that when the pilot looks at the radar display he or she is looking at the same spot on the ground as the EO system whether it happens to be the DAS or EOTS," said Don Bolling.

"We are working on improvements that would ideally place a larger aperture system [a larger aperture behind the window] into the aeroplane for greater detection range whether that for the IRST functionality or for air-to-ground weapons employment." He added: "we have to remain within the volume of the window because that has signature implications but we have looked at getting larger apertures behind that window to increase our effective range.

"The larger aperture system is one of many different capabilities that the US services and partner nations are considering for inclusion in the follow-on development phase of the programme."

On stealth platforms like the F-35 the aircraft's signature must be carefully managed. With IRST the aircraft has a passive IR sensor that creates no emissions unless the laser is used. If the APG-81 radar detects something out at range, using IRST mode the pilot can feed the data to EOTS and passively track the contact with high fidelity while minimizing transmission of RF energy and the aircraft's signature.

The EOTS IRST uses a gimbal, an inertial measuring unit, and a fast steering mirror to provide precise stabilization. Passive in operation, the IRST has a wide area search capability comparable to the APG-81 radar with very high scan and slew rates because of the unique gimbal design.

Looking to future capabilities Don Bolling told *AIR International:* "EOTS is a unique system in that it is able to perform both an IRST scan and traditional targeting FLIR functions. It is the first sensor designed to accomplish this. Since IRST is an inherent part of the EOTS system, we are always looking for ways to provide additional benefits to the warfighter. We have investigated the potential of applying the very fast IRST scan volume across the ground for an IR ground moving target indicator, that capitalises on EOTS' low inertia gimbal design for unique applications in the ISR role."

The EOTS is a two-level maintenance system that enables maintainers to undertake maintenance on the flight line using the built-in test functionality, capable, according to Lockheed Martin, of isolating a single line replacement component (LRC). The EOTS can be dropped down from within its bay to allow maintainers access to replace any one of 15 different LRCs carried.

In March 2011, the EOTS started flying on F-35 mission systems aircraft at Naval Air Station Patuxent River, Maryland and Edwards Air Force Base, California.

The Director Operational Test and Evaluation Fiscal Year 2013 Annual Report, published in January 2014, listed deficiencies with the EOTS that were discovered during flight testing.

The first was line-of-sight stability. Errors in the position of where the TFLIR (targeting FLIR) was pointing over small portions of its field of view were identified and found to be associated with how the gimbal system works. "We have been able to close out the problem," said Casey Contini.

The second concerned system stability that required F-35 test pilots to perform component re-sets. According to Contini, aircraft mission systems are experiencing stability issues while the jet is running on the ground. "They are generally resolved by power cycling the system, so a team from Lockheed Martin's Missiles and Fire Control business is working through the issue.

The third: the EOTS failed to meet target recognition ranges, tracking and stability in portions of its field of view. Contini explained: "This issue is partly related to the instability of the gimbal control, which makes it harder for the pilot to see things, but you also have to take into account the effect of atmospheric conditions with an electro-optical system. You will get different results when you try to test to any atmospheric condition.

"The problem is also in part caused by the inability of the pilot to understand how much detail he needs in order to make a [target] recognition call. Is he trained well enough to recognise and identify a real target versus what he has experienced in the computer model? Training is important because it allows the pilot opportunities to fly in different environments and distinguish them from those used for analysis, the majority of which do not replicate real world environments."

System: **AN/AAQ-40 Electro-Optical Targeting System** Detail: **The A-focal and elevation assemblies of the EOTS** Photograph: **Lockheed Martin**

The fourth: poor image quality, tracking stability and target accuracy. "The objective is to make sure the pilot can see, track and laze the target. We use the EOTS to get a range to the target then hand off GPS co-ordinates generated from an EOTS track. In some cases it worked just fine, but in some portions of the system's field of view it was providing erroneous data, false sets between the known angle of the gimbal and the translation back to the angle of the aircraft. The boresight module created a bias in the system that generated erroneous GPS co-ordinates.

A team from Lockheed Martin Missiles and Fire Control implemented a solution for the abnormalities found in the gimbal control software which were verified by the end of 2012. The only issue not corrected by software, was the boresight module, which required a hardware change.

At the end of last year the F-35 ITFs completed weapons delivery accuracy testing using the

AAQ-37 DISTRIBUTED APERTURE SYSTEM (DAS)

Lockheed Martin claims that the situational awareness provided to a pilot flying an F-35 Lightning II is unparalleled in comparison to that provided by other fighters on the market today. As the second fighter aircraft built in the fifth-generation class, the F-35 is equipped with some very advanced sensors including the extremely capable APG-81 AESA radar with 32 operating modes providing incredible performance according to its manufacturer Northrop Grumman.

But the F-35 is equipped with the revolutionary AN/AAQ-37 Distributed Aperture System (DAS) also built by Northrop Grumman.

The advanced features of the DAS include missile and aircraft detection, track, and warning for the F-35. DAS also gives a pilot 360° spherical day/night vision, with the capability of seeing through the floor of the aircraft. And because the DAS is a passive system, the pilot does not have to point a sensor in the direction of a target to gain a track.

Comprising six infrared (IR) sensors (each housed in an aperture) located around the aircraft, Northrop Grumman classes the DAS as an integrated system and not a sensor or a series of sensors.

The six apertures each provide 95° field of regard and a total of 570° to ensure sufficient overlap in coverage around the aircraft.

One aperture is positioned on either side of the radome below the chine line (the right and left side apertures), one in front of canopy (upper forward), one in front of the refuelling receptacle (upper aft) and two on the under fuselage (the lower forward and lower aft) one pointing forward and one aft, but not straight down.

The six apertures are positioned so that no part of the aircraft masks its view. The system receives threat information from all directions and stitches it together to give a simultaneous three-dimensional spherical view, using that information to protect the aircraft. Consider how a traditional radar scan of less than 200° is displayed on the screen and then you might wonder how Northrop Grumman displays the entire 360° view generated by DAS? Phil Edwards, Business Development Manager for DAS explained: "The sphere provides information on threats and feeds that information to the fusion system, which in turn displays the most relevant information into the HMD. Depending on which direction the pilot is looking will dictate what frames or field of view from the sphere the pilot will be able to see in the HMD."

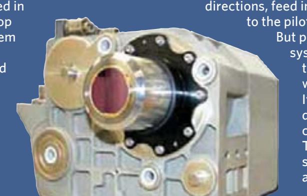
"While the imagery provided to the pilot in the HMD is the most tangible thing generated by the DAS and the one that people are most impressed by, in reality, the ability to simultaneously see different targets in all directions, feed information to the fusion system and provide warnings to the pilot, is the key advantage of the system," he added.

But providing images to the HMD is not the limit of the system's capability. The DAS also tracks airborne targets it detects surface- and air-launched missiles, while providing passive protection of the aircraft.

It performs different functions simultaneously but does not operate in different modes as requested or commanded by the pilot.

The six aperture sensors function in the infrared spectrum in all directions, run advanced exploitation algorithms to increase range, reduce false alarms, turn track information into useable data, feed it to the fusion system and add to the air picture displayed for the pilot.

Each of the six apertures is interlinked to the ICP, which runs the software algorithms that generate geo-registered threat reports and imagery. These are fed to the fusion computer which outputs data using two channels, one to the HMD and one to the Panoramic Cockpit Display.



System: **AN/AAQ-37 Distributed Aperture System** Detail: **An infrared sensor, as used by the DAS** Photograph: **Northrop Grumman**

In the case of the HMD, whatever direction the pilot is looking, he will receive data from the sensor that supports his field of regard. With the Panoramic Cockpit Display, the pilot can chose what he wants presented, which can be a permanent feed from one sensor or whichever sensor can view a given point on the ground, as two examples.

Because some (not all) of the six apertures are located close to hot components on the aircraft, they use an internal cryogenic coolant.

Maintaining the DAS is straightforward because the sensor is laser-welted and permanently sealed and can only be removed and replaced on the flight line. For any kind of repair the sensor is sent back to the depot or Northrop Grumman.

The DAS is designed to detect low intensity threats in a much cluttered background, and has the capability to detect threats such as ballistic missiles. In June 2010, Northrop Grumman collected data from a two-stage Falcon 9 ballistic missile launch from Cape Canaveral in Florida, to determine the applicability of the system to detect, track and potentially target missiles in the ballistic missile defence role. Northrop Grumman's BAC 1-11 test-bed tracked the multi-stage rocket with the DAS for over 808 miles (1,300km) while airborne over the coast of North Carolina.

According to Northrop Grumman's Dave Bouchard, the processing power available enables the DAS to simultaneously track thousands of targets, far more than is possible with any current infrared system.

"DAS is an omni-directional infrared system that can simultaneously detect and track aircraft and missiles in every direction, with no practical limit on the number of targets it can track. DAS truly revolutionises the way we think about situational awareness," said Bouchard.

DAS has three primary functions: missile warning; providing 360-degree situational awareness using an IRST function, and navigation, which is displayed in the Helmet-Mounted Display System visor. The DAS has been in flight test since 2011 and with the Air Force, Navy and Marine Corps fleets since 2013.

The Director, Operational Test and Evaluation Fiscal Year 2013 Annual Report (DOT&E FY2013 AR), published in January 2014, listed deficiencies with the EOTS that were discovered during flight testing.

First was the false alarm rate in the BIT (built in test) reporting. This was an immaturity issue. It was satisfactorily fixed and the false alarm rate has dropped back to its expected level.

Second was the inability of the DAS to distinguish flares from threat missiles. "It's important that the system recognises what is around it and which contacts are friendly: that information was not being provided accurately," said Casey Contini director of F-35 electro-optics and helmet systems at Lockheed Martin.

Third involved a communication fault between the INS and the digital terrain map of mother earth, which caused the DAS to receive erroneous information. Contini explained: "We want to know what's below us, what's ahead of us, so getting the information on a regular basis and without error is crucial. It was important to correct the problem.

The DOT&E FY2013 AR also reported latency in getting information detected by the DAS to the pilot for navigation purposes. Contini said the Joint Program Office had a concern. "It thought the latency measurement should be smaller than the specification supplied by Lockheed Martin. We went to flight test to gather more data for validation. Once the data was to hand, everybody agreed that the requirement as written was sufficient," he said.

Contini says the DAS is in good shape and that Lockheed Martin is waiting for the remainder of the flight test to take place but doesn't expect much to come out at this point. ***Mark Ayton***

System: **Gen II Helmet-Mounted Display** Detail: **A pilot straps the Gen II HMD to his head and connects the system to the aircraft** Photographer: **Paul Ridgway**

EOTS to successfully target GBU-12 laser-guided bombs, GBU-31 and GBU-32 Joint Direct Attack Munitions.

The IRST capability remains in development with Lockheed Martin Missiles and Fire Control. Block 2B will have a limited capability and aircraft configured with Block 3 will have the initial processing power of the PR2 hardware and full IRST capability. Completing the IRST and flight testing the mode will be the focus over the next two years. All other functions of the TFLIR have been fully tested and await verification in the F-35's Block 2B operational test phase. ***Mark Ayton***

Helmet-Mounted Display System

The F-35 is designed without a head-up display (HUD): a system used in fighter aircraft to provide the pilot with flight information. In place of a HUD, the F-35 uses the Helmet-Mounted Display System (HMDS) developed by Vision Systems International.

HMDS comprises a display management computer, a tracker system, and the helmet-mounted display (HMD). The display management computer provides the interface between the aircraft and the HMD, and generates all of the tracker system and display information. The tracker system comprises a magnetic source installed in the crew station and a sensor located on the HMD.

Weighing less than 4.5lb (2kg) including the oxygen mask, the HMD consists of a flight helmet with a noise reduction system, a display unit which provides the pilot with an 'out of the canopy display' to enhance situational awareness, targeting and tracking capability and a day/night sensor to provide video for displaying and/or recording.

The HMD can present video source and symbology commanded by the aircraft's mission computer, but fusion of multiple sensor sources is not a requirement or function implemented in the system. Seven high-speed links including fibre optics and MIL-STD-1394 interfaces provide video and controls.

The HMD is capable of supporting three modes of operation: day symbology only, day video and symbology, and night video and symbology. The modes allow the pilot to continue using the night capability into the dawn and dusk with the HMD day/night camera. Raw data and symbology commands are received by the HMD, most of which are determined by mission system software. Jon Beesley, Lockheed Martin's former chief test pilot for the F-35, who flew the maiden flight on December 15, 2006 spoke of the elegance of HMD saying: "Most HMDs have to sacrifice either the symbology or night vision. In ours you won't".

The HMD provides accurate head orientation and position data to the mission computer while the aircraft's data fusion engine and the pilot-vehicle interface automatically display air and surface targets on the HMD generated by any of the F-35 sensors. The data fusion engine controls and prioritises which targets are displayed on the HMD.

The APG-81 Active Electronically Scanned Array radar sends all contacts to the integrated core processor, which tasks them to the mission system for processing and displays the screen on the HMD. In addition, the HMD uses line of sight commands to cue the radar.

The first version of the HMDS called the Gen II, which is being used on F-35s in the System Development and Demonstration phase, demonstrated a number of test deficiencies such as display jitter, reduced night vision acuity and display latency.

By 2012 the problems encountered with the Gen II HMDS had caused such significant concern within the F-35 test community that the Joint Program Office (JPO) awarded a contract to BAE Systems to work on an alternative system that featured detachable night vision goggles. However, in late 2013 the JPO – with a desire to have a single helmet design – issued a stop work order to BAE Systems because VSI was demonstrating good progress with its upgraded Gen III version of HMDS. This latest version incorporates software fixes designed to correct latency issues, a new ISIE-11 night vision camera and liquid crystal displays. Gen III HMDS is expected to be available for LRIP 7 aircraft in 2016. ***David C Isby and Mark Ayton***

System: **Gen III Helmet-Mounted Display** Detail: **The upgraded Gen III HMD fitted with an ISIE-11 camera** Photograph: **Rockwell Collins**

Targeting Revolution

Mark Ayton details the F-35's revolutionary AAQ-40 Electro-Optical Targeting System

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Multi-capable

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Above: The aft end of the faceted window assembly showing three of the seven sapphire panels. Lockheed Martin
Opposite: The EOTS faceted window assembly is clearly seen under the forward fuselage of F-35A 07-0744. Scott Fischer

significant challenge," Don Bolling extolled.

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Optics and Components

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Opposite Top: ***This shot shows the A-focal and elevation assemblies of the EOTS.*** *Lockheed Martin*
Opposite Bottom: ***The colour of the sapphire panels is clearly shown in this side shot of the EOTS faceted window.*** *Lockheed Martin*
Below: ***Sabreliner 60 N11LX was leased by Lockheed Martin for flight testing of the AAQ-40 EOTS.*** *Lockheed Martin*

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Programme

Development of the EOTS sensor was completed at the end of September 2010 as part of the F-35 system development and demonstration phase. Much of the EOTS flight testing was completed on Sabreliner 60 N11LX leased by Lockheed Martin and flown from Goodyear, Arizona. Operated with a crew comprising pilot and co-pilot, and in the back end a sensor operator and a flight test director, the aircraft first flew with the sensor installed in May 2007.

In late May 2010, the EOTS undertook ground taxi tests followed by flight testing on Lockheed Martin's Boeing 737 CatBird test bed. Fitted with the DAS, the APG-81 radar, the ESM (electronic support measures) suite, the CNI suite, an F-35 cockpit and engineer test stations in the back, CatBird can test all sensor fusion and is set-up to exactly replicate what the pilot will see in the F-35. To provide transparency to the pilot sitting in the test cockpit onboard the CatBird during flight, the EOTS is installed behind a window in exactly the same way as on the F-35.

In March 2011, the EOTS commenced flying on F-35 mission systems aircraft at NAS Patuxent River, Maryland and Edwards AFB, California.