CEC: Sensor Netting with Integrated Fire Control

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The Cooperative Engagement Capability (CEC) is one of the first network-centric systems that encompasses sensors and weapon systems used in U.S. Navy battle forces. When it is successfully integrated with the air defense systems of the other services, it will serve as the foundation for a single integrated air picture and for weapons employment in future Joint architectures. This article provides a brief description of the sensor netting and integrated fire control concepts conceived and developed primarily by APL that are embodied in CEC today; reviews recent events in the development, demonstration, test, and evaluation of these concepts; gives an overview of recent test events, results, and conclusions; and previews advanced concepts that are being explored for the future.

INTRODUCTION

The Cooperative Engagement Capability (CEC) is a spin-off from the Battle Group Anti-Air Warfare Coordination (BGAAWC) program (see the article by Lee et al., this issue) in which many of the fundamental and necessary CEC concepts were demonstrated incrementally. The CEC program incorporated, improved, and systems engineered these BGAAWC capabilities and others into the present CEC, including a unique architecture, equipment set, computer programs, and test and development as described later. These capability demonstrations facilitated the development of signal processing, gridlock, autocorrelation, automation, link protocol, combat system integration, and operational procedures.

CEC passed its Operational Evaluation (OPEVAL) in 2001 with flying colors, and with it came a dramatic improvement in the ability of U.S. Navy ships and aircraft to defend the battle force against difficult air threats by maximizing the effectiveness of existing sensors and weapons, i.e., sensor netting with integrated fire control. CEC enables the sharing of radar and identification, friend or foe (IFF) data across CEC units, resulting in a real-time, distributed fire control quality picture that is common on all units. CEC provides a quantum improvement in track picture consistency across the force with enhanced track accuracy, track continuity, and identification (ID) with IFF concurrence. It also has the potential to provide the same enhanced capability to the air defense systems of the Marine Corps, Army, and Air Force.

Put simply, CEC is intended to (1) net the sensors of a force together in a manner that maximizes their effectiveness at maintaining a continuous track on all aircraft and missiles in the area of interest and, when necessary, (2) enable one unit to provide fire control quality information to another unit when the shooter is unable to track the threat with local sensors. This is a very powerful combination of capabilities.

Against the most stressing threat aircraft and anti-ship missiles, CEC expands the battlespace significantly. By providing a continuous track on these air threats from their initial detection, CEC gives the commanding officer minutes instead of seconds to identify and engage the threat. Furthermore, CEC enables any unit that is equipped with an area surface-to-air missile to engage and destroy the threat, regardless of whether that unit has local sensor information on it.

The CEC design maximizes the effectiveness of existing and future battle force sensors and weapon systems through force network operations. It enhances force coordination and cooperation by providing automation and better information to command and decision makers. CEC furnishes these capabilities of force cooperation while maintaining the autonomy of the individual ship-, aircraft-, and land-based units.

CEC has undergone extensive demonstration and testing over the last 12 years.[1] In addition to the OPEVAL mentioned perviously, CEC also underwent a Technical Evaluation (TECHEVAL) in 2001. During TECHEVAL, CEC satisfied all of its critical technical performance requirements; and as a result of the OPEVAL, the Commander, Operational Test and Evaluation Force (COTF), declared that CEC was operationally suitable and operationally effective. These conclusions will support a decision to start full-rate production of the CEC equipment set and the fielding of CEC on all major Navy air warfare and amphibious assault command ships. These tests showed conclusively that CEC meets its systems requirements by continuously tracking difficult air threats in a stressing environment; providing a robust, consistent track picture across all CEC participants; and enabling the transfer of fire control quality track information among ships so that those not able to see the threat with local sensors can still engage it with their surface-to-air missiles.

The terms “network-centric” and “single integrated air picture” (SIAP) were coined long after the initial concepts for CEC were formulated and the requirements for the system defined. Because of recent DoD interest in the transformation of the services, there has been considerable discussion on whether CEC is network-centric or provides the SIAP. CEC embodies many of the characteristics of a network-centric system in that it maximizes the effectiveness of existing and future sensors and weapon systems through coordinating and sharing information and air defense system commands via a network. Similarly, because of its capability to provide a robust, consistent, and sensor quality track picture across all participants, CEC can serve as the foundation for an SIAP. It is, however, only one contributor to the force track picture. Information from additional sources such as tactical digital links (Link-11, Link-16) and other onboard and offboard sensors must be combined with CEC data to create a complete SIAP.

CEC is badly needed by the Fleet today to counter difficult threats in a stressing tactical environment. Given that it has been shown to meet its operational requirements and provide the Fleet with a significantly expanded battlespace as well as a corresponding increase in reaction time against the threat, it will be fielded in all Navy battle groups as soon as possible.

But although it is very capable, the current implementation of CEC in the Navy is only the beginning of what is possible using sensor netting. Sensor netting, when taken to its fullest potential, will provide far more information than is available from surveillance radar and IFF systems today. It will not only track aircraft but also characterize them more fully so that their identity can be determined when it is critical. This is the promise of sensor netting in the future.

The state of CEC in the Fleet today is much akin to the early introduction of the Internet. When the Internet (then called ARPAnet) was first introduced, it was implemented by connecting existing computers at different sites to exchange information. Although this proved useful, making these connections was awkward and often difficult to accomplish with the then-existing computer systems. It was not until computer architectures were redesigned to incorporate network servers as a natural part of the system that the Internet became a seamless part of normal computing services.

CEC’s integration with existing ship and aircraft combat systems is in a similar state of development. It has been added to combat systems that were designed to operate autonomously with some limited exchange of sensor information and coordination of actions with other units. Even though CEC provides a comprehensive composite track picture to the combat system on each unit, the combat system’s ability to fully exploit this information is still somewhat limited because the system interfaces are constrained by the existing combat system design.

SENSOR NETTING

Since its invention, radar has been the primary sensor for detecting and tracking the position of aircraft and missiles in the airspace around the battle force. No single radar is capable of detecting and tracking all aircraft and missiles in the air at all times. The effects of the natural environment alone preclude a radar from seeing all of the air objects because of fading, multipath, terrain obscuration, etc. The radars in a force instead form and lose tracks on aircraft in the surveillance area. Operationally, this means that the commander of an air defense system is faced with intermittent air tracks that do not last long enough for him to decide on their ID, and with threats that pop up close in, leaving little time to react to them.

Furthermore, each ship, aircraft, or land air defense system creates a different air track picture based on what it sees with its radars and other sensors as well as the information exchanged over Link-11 and Link-16. These different pictures make it very difficult to coordinate the response of the force to threats because the various units cannot agree on what the situation is. Lack of force coordination leads to reduced effectiveness in defending against the threat because some threats will be overengaged, which leads to reduced sustainability, and others may slip in unengaged, which leads to reduced survivability.

Sensor netting is intended to maximize the effectiveness of existing and future radars and other sensors by fundamentally changing the way that the sensor information is exchanged across the force and processed by each unit. As shown in Fig. 1, CEC exchanges information from individual sensor measurements rather than reporting tracks, which are formed by filtering multiple measurements. Typically, it takes a radar several "hits" to form a track; sometimes the radar does not receive enough of these hits on a given aircraft or missile to establish a track. In other cases, even after establishing a track, the radar loses it because of phenomena mentioned earlier. CEC overcomes this by netting the sensor measurements from all of the radars together such that, once any sensor in the force detects the threat and establishes a track on it, all force radar measurements that are associated with that threat can contribute to maintaining the track, even if the originating sensor loses it some time thereafter.

When one of the surveillance radars establishes a track in CEC, that information is used to "seed" the network by distributing a track start notification over the network along with the associated measurement reports (AMRs) for that track. If the track is tactically significant, other radars in the force are cued (or gated) to acquire it by increasing the sensitivity of the radar processing in that specific location to enhance the probability of being able to acquire the target. Radar measurements from other sensors that are associated with the new track (AMRs) are distributed to all other units, where they are combined with local data to form a composite track. At this point, CEC can maintain continuous track on an aircraft if there are enough updates from the various radars—even though no single radar has firm track on it.

CEC assures that the sensor netting process results in a consistent track picture on all units by using common alignment, association, and tracking processes and by distributing the associated measurements to all units in the network. This process only works if the remote data are received locally on each unit with an accuracy that is commensurate with the sensor providing the data. Therefore, extremely accurate alignment processes are needed to register and align the remote data in the receiving ship's coordinate frame. These gridlock processes have been demonstrated to stay within tolerance levels in both dense and sparse tracking environments and under a variety of tactical scenarios.

Sensor netting takes advantage of the different positions of the radars in the force and their diversity in frequency, scan rate, and signal processing to overcome the limitations of any single radar. The network tracking process allows the force to capture and use many of the sensor measurements that would have been discarded by single sensors. Therefore, the resulting track picture is more continuous, complete, consistent, and accurate.

The following attributes of sensor netting are fundamental to this process:

- Collect and distribute all sensor-derived information from the primary surveillance and fire control sensors such that the superset of sensor-derived knowledge is available at all participating units
- Preserve original sensor data precision and accuracy to enhance information correlation and, when of sufficient accuracy, support laying of ordnance
- Extract sensor information from individual sensors cooperatively that could not have been extracted from an individual sensor on its own
- Assemble a composite of data into a track of qualities (accuracy and longevity) beyond the capability of any individual contributor (Fig. 2)

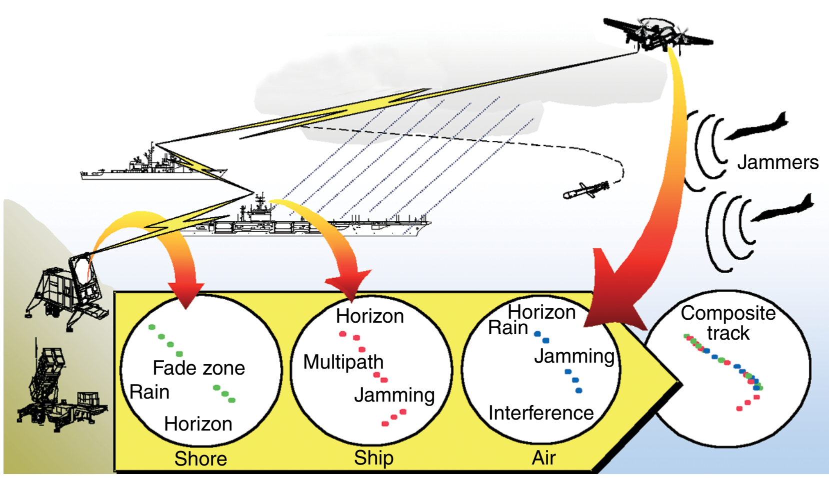

Figure 1. The sensor netting composite tracking concept provides a coherent, highly accurate track picture held by all units in a common, shared database. CEC nets sensors, exchanges sensor measurements among all netted sensors, and fuses data to create a composite track accuracy.

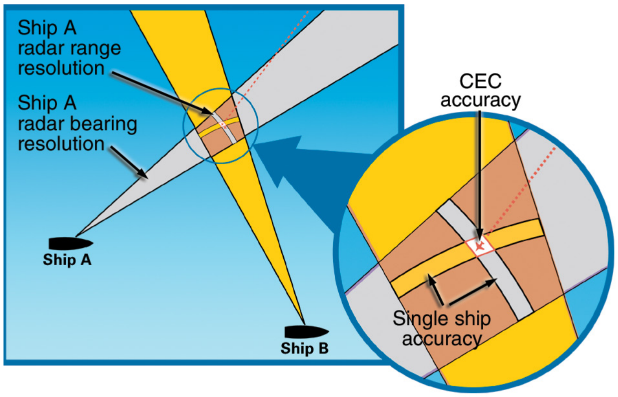

Figure 2. Sensor netting significantly increases track accuracy (radar is more accurate in range than bearing).

CEC was designed to incorporate these attributes of sensor netting, thereby overcoming the limitations of single radars. This does not obviate the need to continue to improve the performance of the radars themselves. In fact, as new sensors are introduced in the Fleet, sensor netting enables all units in the network to take advantage of the improved performance of the new sensors, even when they are installed on only a few ships or aircraft. This is one of the significant force-multiplier effects of sensor netting.

INTEGRATED FIRE CONTROL

Once a composite track picture is established on the CEC network, it is provided to each of the local combat systems of the participating units. This information can be used to coordinate the response of all units in the network, thereby optimizing the use of available assets to ensure that all air threats are engaged without wasting missiles on overengagements. The current algorithms implemented in CEC alert all of the other units when a ship decides to engage a threat. This allows the others to defer engaging that particular aircraft or missile until the outcome of the other missile engagement is determined. Conversely, the other ships are not precluded from also continuing to engage that threat if such action is dictated by the threat's proximity.

One limitation of ship combat systems without CEC data from other ships is that they can engage only threat aircraft and missiles that they can detect and track with their local fire control quality radars. An aircraft carrier or amphibious command ship equipped with a self-defense system such as the Rolling Airframe Missile or NATO SeaSparrow Missile can only begin to engage a low-flying threat after it has broken the radar horizon. Given the supersonic speeds at which some anti-ship cruise missiles travel, the time it will take to detect, track, identify, and decide to engage the threat may limit the number of engagements, with a corresponding reduced probability of kill.

An Aegis cruiser or destroyer can only engage the incoming threat with an area defense weapon such as Standard Missile if it can detect the threat with its AN/SPY-1 radar. SPY is the source of all fire control quality tracking information used to initialize Standard Missile, fire it, provide it midcourse guidance, and perform terminal illumination of the target. If the ship under attack loses the threat track during the attack because of countermeasures or the natural environmental phenomena mentioned previously, it cannot even begin to engage the threat until the track is reestablished. This could be disastrous if the track drops at the wrong time.

The integrated fire control capabilities of CEC allow ships to overcome these limitations. When integrated with self-defense systems, CEC provides cued engagements (Fig. 3), where the CEC composite track of the incoming threat is used to cue the self-defense system to the threat's location and identity even before it breaks the ship's radar horizon. This cue allows the ship commander to engage the threat earlier and the self-defense fire control radar to acquire the track right at the horizon, thereby maximizing the range of the first engagement and possibly allowing enough time for a second engagement if needed. This greatly increases the probability of killing the threat before it reaches the ship.

With area defense systems like Aegis, CEC provides an engage-on-remote capability (Fig. 4) that allows one ship to decide to engage a threat; initialize, fire, and do midcourse guidance of a Standard Missile toward the threat; and perform terminal illumination of the threat with a fire control illuminator for terminal homing by the missile, all based on fire control quality radar information provided by a remote ship. In this mode, all of the missile control functions can be performed by the firing ship before the threat reaches its radar horizon. The final intercept can occur just as the target breaks the horizon and can be illuminated by the firing ship.

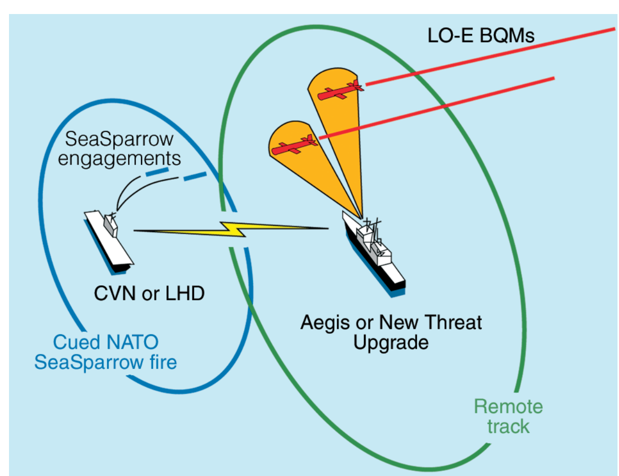

Figure 3. Cued self-defense engagements (LO-E = low elevation).

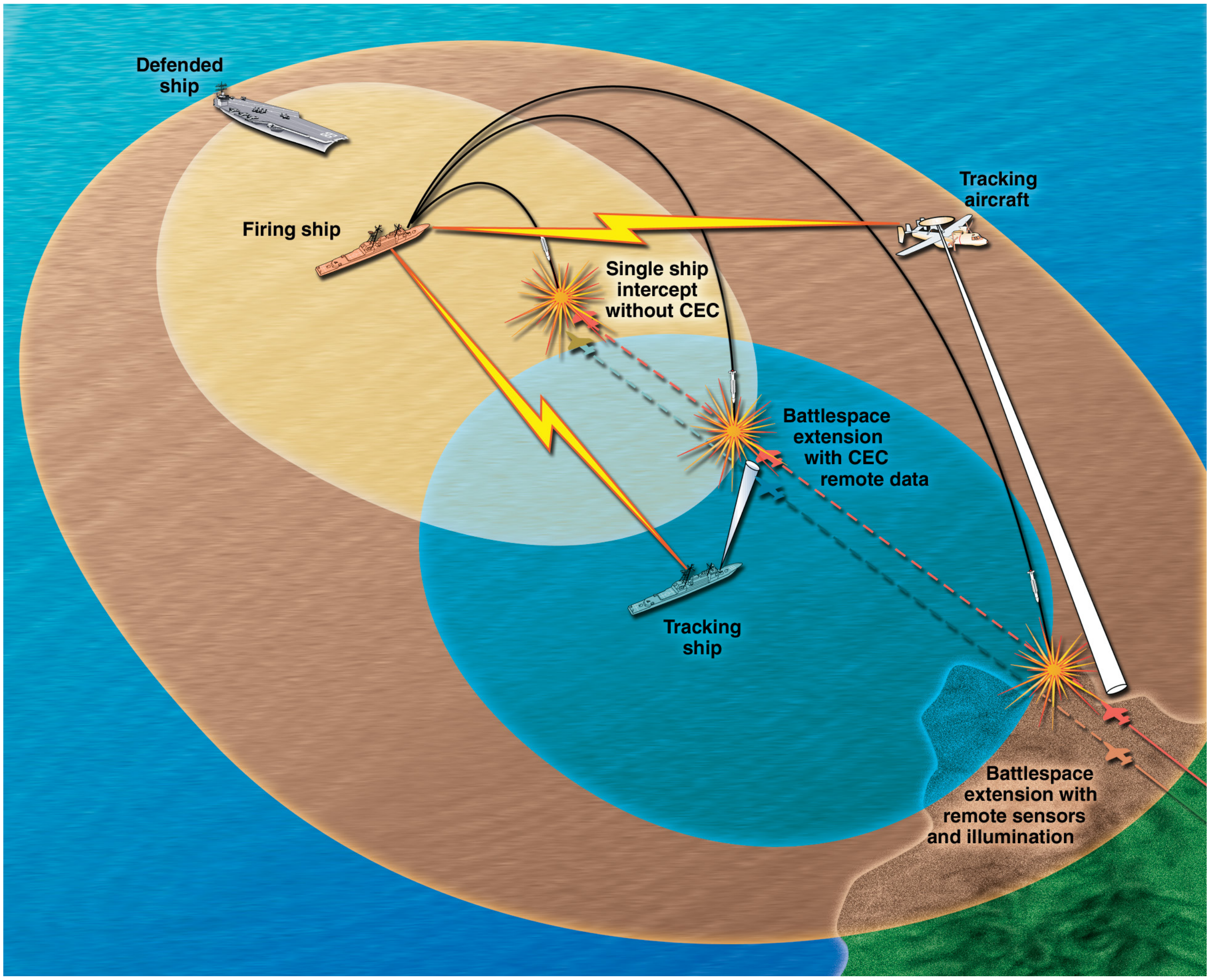

Figure 4. Battlespace extension through CEC. A single ship must wait for the attacker to cross its radar horizon to engage, thus delaying intercept until the attacker is close to the ship. With CEC the ship can fire before the attacker has crossed its horizon using tracking information from another ship. This enables illumination for an intercept at the firing ship's horizon. Intercept beyond the firing ship's horizon is possible using remote data and illumination from another ship, aircraft, or extended-range missile with an active seeker.

Engage on remote also significantly expands the battlespace by allowing ships to engage the threat earlier than they would otherwise be able to do, if at all.

Future missions such as the Navy Integrated Fire Control-Counter Air will allow ships to fire Standard Missiles at targets over the horizon based on information received from remote units. This will require an active seeker in a Navy extended-range missile or remote (airborne) fire control illuminators such as those proposed in the Joint Land-Attack Cruise Missile elevated netted sensor aerostat to guide semi-active seekers in the Standard Missile to the target.

COMPOSITE IDENTIFICATION

A complete radar picture of the airspace is necessary to support air defense operations, but it does not yield sufficient information on which to make the decision to engage an air track that may be a hostile aircraft or missile. In many cases, the inability to correctly identify the track leads to a ship being unable to engage air threats in time or to a ship launching a surface-to-air missile at a nonhostile aircraft. The lack of verifiable ID information results in many conflicts on the force data links as to the interpretation of the track ID. These conflicts are a major contributor to force interoperability problems. The ID problems are so severe that they can preclude units from defending themselves. For example, if a ship is in the process of engaging an inbound air track that it has decided is a hostile aircraft, that engagement will be stopped if another unit on the data link reports the same track as a friend (even if this ID is in error). This can lead to fatal consequences if there is not enough time for the ship to reengage the threat before it reaches its target.

One source of ID information is IFF data. IFF provides information on friendly aircraft that are willing to respond to IFF interrogations. One of the leading sources of ID errors and conflicts is in the correlation of IFF data to radar tracks. The IFF data are inherently inaccurate when compared to radar data. In many cases, an IFF return could correspond to several different radar tracks that are near it. Unfortunately, the correlation processing in many of the older combat systems correlates the IFF returns to the wrong radar track or swaps IFF returns between two crossing radar tracks, which leads to an inappropriate ID being assigned to an air track. This can cause an air defense system to engage the wrong aircraft.

Another source of ID conflicts in a force is due to different ships and aircraft using different rules to decide the ID of an air track. These rules take into account such factors as the IFF response of the aircraft; its location, altitude, speed, and heading; and perhaps point of origin if it is known. Obviously, if the ships and aircraft in a battle group use different rules to assess the air tracks, they will come to different conclusions on the ID of the tracks. This leads to numerous ID conflicts on data links and causes a large part of the link bandwidth to be used for ID conflict resolution.

During CEC testing in 1994 aboard the USS *Eisenhower* battle group, it was recognized that the comprehensive radar track picture offered by CEC sensor netting could not be fully used unless the ID conflicts and errors could be managed. It was decided to incorporate IFF response processing into CEC, thereby using the vantage point of several ships in the network to better localize the position of the IFF response so that it could be accurately correlated to radar tracks. For those cases where ambiguity still existed, CEC would not correlate the IFF to any radar track but would track it separately until an assured correlation could be made.

To mitigate the effects of different rule sets being applied to the track picture by the ships in a force, CEC implemented a force-wide distributed doctrine (automated rules) processing capability that allowed the battle group commander to distribute a common doctrine set for use by all units in the network. This combination of IFF data processing and force-wide automated doctrine processing was called Composite ID.

Composite ID automatically evaluates the entire track file periodically to assess the ID for each air track. This ID is shared as common information throughout the CEC network. The Composite ID process provides ID recommendations to the ship combat system, which can then decide to accept or modify the ID.

This system is only as accurate as the rules, which are established in the doctrine set, and the availability of IFF information. Therefore, Composite ID is much better at identifying friends than hostiles. Even so, Composite ID is still extremely useful because it focuses the attention of the ID supervisor on unknowns that are potential hostile aircraft rather than having to sort through all of the friendly aircraft as well. The Composite ID algorithms and design were derived from the Automatic ID systems that had been installed on aircraft carriers in the 1980s and 1990s.

SYSTEM CONFIGURATION

CEC has two major subsystems: a robust high-bandwidth Data Distribution System (DDS) and a computationally intensive Cooperative Engagement Processor (CEP), which are both installed on all CEC participating units (Fig. 5). Early experimentation showed that the only way to maintain continuous track against difficult maneuvering aircraft and missiles in a stressing environment was to distribute AMRs instead of tracks or tracklets among the units. Furthermore, these AMRs had to be received at each unit with an accuracy that was commensurate with the sensor providing the data. This required that the DDS be able to exchange a significant volume of radar data among the units with very low latency. Given that CEC was to be installed on Aegis ships and would be used to transfer fire control data among ships, the DDS also had to be robust enough to maintain connectivity among ships and aircraft at normal separations in the same jamming

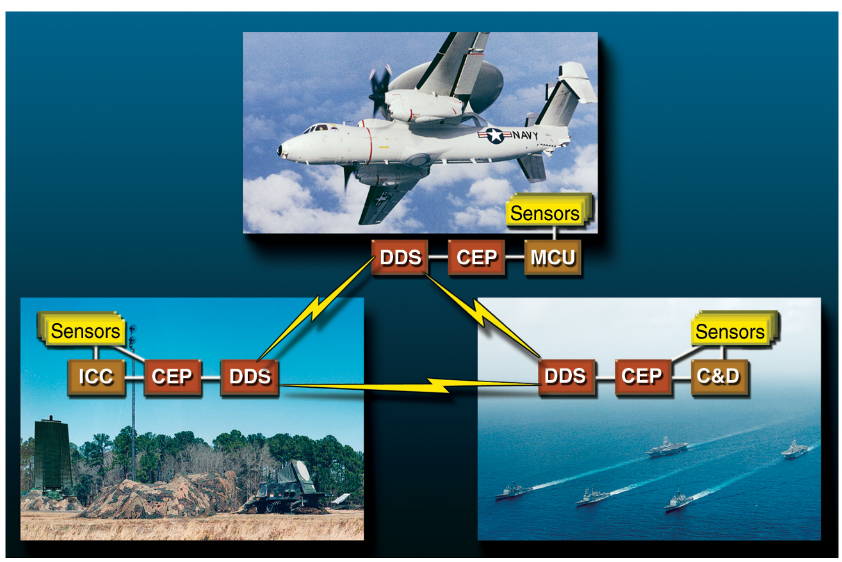

Figure 5. Cooperative Engagement Capability (C&D = Command and Decision, ICC = Information Coordination Central, MCU = Mission Computer Upgrade).

environment for which the Aegis AN/SPY-1 radar was specified.

These requirements led to a very robust DDS design, which used directional beamforming antennas to create scheduled pair-wise connections among the ships and aircraft to transmit large amounts of data and maintain high-quality connectivity in the face of heavy jamming. To further enhance its immunity to jamming and reduce its probability of intercept and exploitation, the CEC signal is also frequency-hopped through its band. The selection of the DDS transmission frequency band was made through a trade-off of throughput, connectivity quality, and environmental resistance requirements versus available bandwidth within a frequency band. The DDS is one of the most robust, capable, and high-quality radio-frequency network systems available today.

No matter how high the throughput of the DDS, there are scenarios under which the combination of number of tracks in the air and number of units on the network could theoretically exceed the DDS terminal throughput. CEC processing automatically recognizes when this threshold is reached and invokes a pruning process that eliminates the reporting of redundant radar measurements that do not enhance the estimate of the track position. This determination is done through a trial track processing filter at each of the transmitting units, which prevents unneeded reports from being sent when the network reaches capacity. This approach has been shown to maintain the highest-quality track estimate at each CEC site while conserving network throughput capacity when needed.

Significant CEC testing, under a variety of settings and network architectures, has shown that the CEC DDS capacity will handle the tactical track loads and number of CEC units for a very large force spread over a theater. Modeling and simulation has shown that even the largest envisioned CEC network in Joint force scenarios still remains within the capacity of the DDS terminal.

The CEP needed a powerful processing capability to be able to process the AMRs from all of the radars in the network as well as local radar data. It was recognized that the AN/UYK computer architecture used in ship combat systems at that time would not meet these requirements. Therefore, a scalable, multiprocessor architecture was pursued that would be able to keep up with the multiple radar data streams and process them in real time, providing a composite track picture to the combat system with subsecond latencies.

The architecture chosen was a commercial off-the-shelf (COTS) design that used multiple processor boards in a card cage with VME back planes (Fig. 6). This design lent itself to being ruggedized for shipboard and airborne use while applying the processing power of commercial processors. The architecture was scalable because additional boards could be added if more processing power was required for future applications.

Interface converters are used to convert the shipboard system legacy interfaces into the commercial standard interfaces used within the COTS equipment set. This allows all of the computation in the CEP to be done in an open systems, commercial standards–based processing environment.

This enduring architecture has gone through several COTS refresh cycles in which the processor boards have been replaced by the next generation of processors and memory. The system started with the Motorola 68020s and is currently using the commercially available PowerPC boards. The increasing speed of the processors has led to a decreased board count over time, even though functionality and processing requirements have grown. New alternative processing architectures are being examined as they become available for future CEP application.

The original preproduction equipment sets were created in a cooperative effort between APL and E-Systems, ECI Division (now Raytheon, St. Petersburg, Florida). The original equipment set, weighing more that 10,000 lb, was installed and tested in ships of the *Eisenhower* battle group starting in 1990 (Fig. 7). The production shipboard equipment set, designated AN/USG-2(V), now weighs on the order of 3000 lb and is also produced by Raytheon.

The equipment set was installed in ships of the USS *John F. Kennedy* battle group and tested at CEC

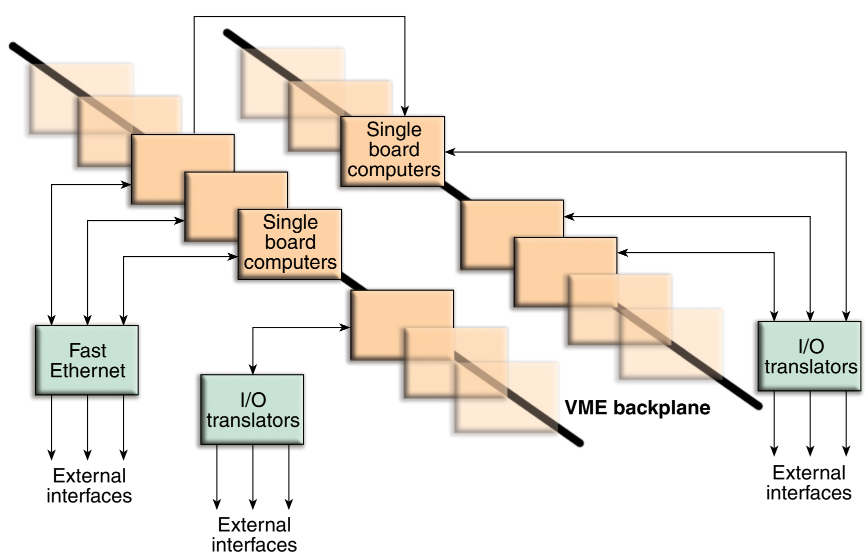

Figure 6. CEC computer architecture.

Figure 7. From left to right, AN/USG-1, -2, and -3.

OPEVAL. An airborne version at around 700 lb, designated AN/USG-3(V), has been installed on the first test E-2C aircraft and is undergoing testing this year. The size, weight, and power requirements of CEC equipment are expected to continue to shrink with the availability of advanced processing architectures that will lead to further applications such as a land-mobile system for the Marine Corps and perhaps the other services.

One example of recent innovation provided by APL is the application of new active array technology to the CEC active aperture antenna. In 1999, APL proposed a new array technology that used lower-power, active element transmit and receive modules, resulting in a more flexible and affordable antenna array design. A prototype design was fabricated by the Laboratory to prove out the concept. This technology was then transferred to the prime contractor for use in a new shipboard planar array antenna which has the potential to save the government over $600 million for CEC antenna procurements for Navy ships alone.

The computer program architecture was as innovative as the equipment design. To harness the processing power of a multiprocessor system, CEP engineers designed a common genealogy architecture infrastructure (CGAI) that supported the ability to distribute the computing across approximately 30 processor boards in real-time processing. CGAI provided common messaging and timing services for the application programs found in "middleware" in most systems today. CGAI has allowed CEP application programs to be rehosted to new-generation processor boards with minimum modifications to the computer application programs themselves.

The CEP computer programs are divided into kernel processes and adaptive layer processes. Kernel processes include those application programs that are central to the sensor netting process and are required to be identical in all CEPs at all CEC participating units. Adaptive layer processes are those that are specifically tailored to the radar, IFF, and combat system interfaces on the ship, aircraft, or land-based unit on which the CEP is installed. The adaptive layer takes the information provided by the radars and IFF and formats and conditions the data for processing by the kernel processes as well as distribution to the other units via DDS. This allows CEC to be integrated with a number of different combat systems with minimum modification to the legacy combat system elements. The result was significant cost and time savings during system development.

Future combat systems should be designed to use sensor netting. This would lead to a common set of sensor interfaces with the sensor netting function and a reduced need for the adaptive layer. In the current implementation, the adaptive layer is collocated in the CEP with the kernel processes. Future architectures could migrate the adaptive layer to the location where sensor processing is performed or to network servers that provide the sensor measurement data. These approaches have already been demonstrated in systems like the Ship Self-Defense System.

The rapid development of these capabilities required the codevelopment of two system development tools that are not part of the fielded CEC equipment or computer programs. The Wrap Around Simulation Program (WASP) was developed to allow CEP developers to simulate the interfaces that the CEP would expect to see in the tactical environment. WASP replicates the interfaces in a controlled environment where the CEP developers can mature and troubleshoot the computer programs before testing with the actual equipment and interfaces. WASP enabled testing and troubleshooting at the application, subsystem, system, and multisystem levels and therefore facilitated rapid development and testing of the CEP. It also supported the replay of data collected during actual use of the system at sea to support problem isolation and correction in the laboratory.

From the very beginning, the CEP was instrumented with a powerful data extraction capability that allowed data to be stored so that the developers could determine if the complex processes were being performed correctly and within the specified performance range. A set of data reduction tools was developed that provided unique insight into the network and distributed processing system performance. These tools, using modern graphical user interface displays, were so effective that, in many data analysis situations, they allowed the CEC engineers to correct their own system problems immediately (saving significant test time and cost) and diagnose problems resident in the combat system elements to which CEC was interfaced before they could be determined by the combat system engineers themselves. As a result of its effectiveness, this data extraction/data reduction approach has been adopted in a number of other systems.

RECENT TEST EVENTS

Sensor netting was first demonstrated in CEC during land-based and at-sea exercises in 1989 and 1990, respectively; a robust battle group sensor netting capability with integrated fire control was demonstrated in 1994 aboard the *Eisenhower* battle group.[2] On the basis of the overwhelming success of these events, it was mandated by Congressional Language that CEC should be fielded in an initial operational capability by 1996. To achieve this, the program set about to perform independent verification and validation of the preproduction prototype equipment sets and computer programs that were installed on the *Eisenhower* battle group. This effort was completed by the end of September 1996 aboard USS *Anzio* (CG 68) and USS *Cape St. George* (CG 71).

During that same period, the CEC prime contractor (now Raytheon, St. Petersburg) was building the production shipboard equipment set, AN/USG-2. This set was first installed on USS *Wasp* (LHD 1), an amphibious command ship, and tested in an Initial Operations Test and Evaluation (IOT&E) held during the summer of 1997. During IOT&E, CEC was tested on the *Wasp* with the newly installed Advanced Combat Direction System (ACDS). The ship, stationed in the Virginia Capes Operating Area, was networked via CEC and Link-16 with the land-based Aegis Weapon System (AWS) at the Aegis Combat System Center, Wallops Island, Virginia, and a land-based ACDS at the Fleet Combat Direction Support Activity, Dam Neck, Virginia.

The testing showed that, although CEC was essentially operating as designed, the combination of CEC, ACDS, and Aegis at the different sites created numerous interoperability problems when Link-16 and CEC were used simultaneously. These problems were later traced to a combination of existing link processing issues in the combat systems and incongruent approaches used to integrate CEC in ACDS and Aegis.

Subsequently, ACDS failed its OPEVAL. At the same time, the Aegis Baseline 6 Phase 1 Combat System, which was undergoing initial testing, was found to be not mature enough to be operationally fielded on USS *Vicksburg* (CG 69) and USS *Hue City* (CG 66). Because these ships were planned to support CEC OPEVAL during the summer of 1998, it became apparent that there would be insufficient time to mature the new combat systems and perform the necessary integration testing of these combat systems with a new CEC baseline. Faced with this uncertainty, the Program Executive Officer for Theater Surface Combatants (PEO(TSC)) decided to delay the CEC OPEVAL until 2001 so that a disciplined approach could be taken to complete and test the combat systems, integrate and test CEC, and resolve as many of the interoperability problems as possible.

What followed became known as "the road to OPEVAL," which involved 2 Navy battle groups and over 10,000 sailors and airmen in 10 major underways over a period of 3 years. During the last year alone, there were 45 days of testing on the range with 10 warships, 439 aircraft sorties (Navy, Air Force, Marine Corps, and civilian), 74 drone (surrogate threat missile) presentations, and 30 live surface-to-air missile firings. The government and civilian test team consisted of over 500 personnel involved in test planning, execution, postevent analysis, and system modifications. During the 3-year period, the combat systems were brought to operational maturity; CEC was integrated with the combat systems and thoroughly tested, both technically and operationally; and many of the known major interoperability problems were mitigated through procedural changes and changes to the combat systems.

Although APL played many roles in the preparation and execution of these events, one of the most unique and important roles was the technical verification of the test scenarios that would be used for tracking and live missile firings. The Laboratory's unique ability to model the performance of the sensors and weapons with high-fidelity simulations that take into account the environmental conditions that could be encountered proved to be invaluable. Lessons learned from previous battle group testing showed that it was critical to do high-fidelity predictive analysis before each event to know what results were expected. In many cases, potential failure due to unforeseen effects of the environment was averted because of the knowledge gained from the predictive analysis. This saved millions of dollars that could have been lost in test assets had the missile exercises failed.

In February and March 2001, CEC TECHEVAL was conducted with the *John F. Kennedy* battle group in the Puerto Rico Operations Area and the Virginia Capes Operations Area, respectively. Figure 8 shows a representative scenario used during TECHEVAL in the Puerto Rico Operations Area where the battle group was subjected to attack by multiple air- and land-launched anti-ship cruise missiles while under simultaneous electronic attack by the Big Crow aircraft. Based on the results of TECHEVAL and the preceding tests, PEO(TSC) certified CEC's readiness to proceed to OPEVAL. Some noteworthy observations from the TECHEVAL were as follows:

- The ability of the battle group to defend against threats that surpass single-ship capability was consistently demonstrated.
- Countering demanding targets (low, fast, small) and stressing environmental conditions magnified the improvement afforded by CEC to the battle group.
- CEC network availability and stability were so consistent that they were transparent to operations.
- All reliability, availability, and maintainability system requirement thresholds were consistently surpassed.
- CEP track file concurrence, an important SIAP enabling feature, was consistently demonstrated at near-perfection levels.

Figure 9 shows a example of the composite picture provided by CEC during TECHEVAL on 27 February 2001 in the Virginia Capes Operating Area.

In April and May 2001, COTF conducted CEC OPEVAL, the largest, most complex, and operationally representative test ever conducted by the Navy. The events were again held in both operational areas over 18 days of at-sea testing with 10 warships, 198 dedicated aircraft sorties, 43 drone presentations, and 29 missile firings. COTF personnel directed simultaneous attacks against the battle group using aircraft-launched high-diving anti-ship cruise missiles; multiple land-launched, sea-skimming anti-ship cruise missiles; stand-off jammers; and other countermeasures. Throughout these scenarios, CEC showed the ability to significantly increase the battlespace by allowing the battle group to establish and maintain track on the threats much earlier than would have been expected without CEC. This allowed the commanders much greater time to identify the threats and successfully engage them before they reached their targets.

No system has undergone the breadth and depth of technical and operational testing that CEC has been through in the last 3 years. CEC has consistently demonstrated enhancements to the battle group's ability to defend itself against the most stressing air threats across many different types of scenarios, threat aircraft

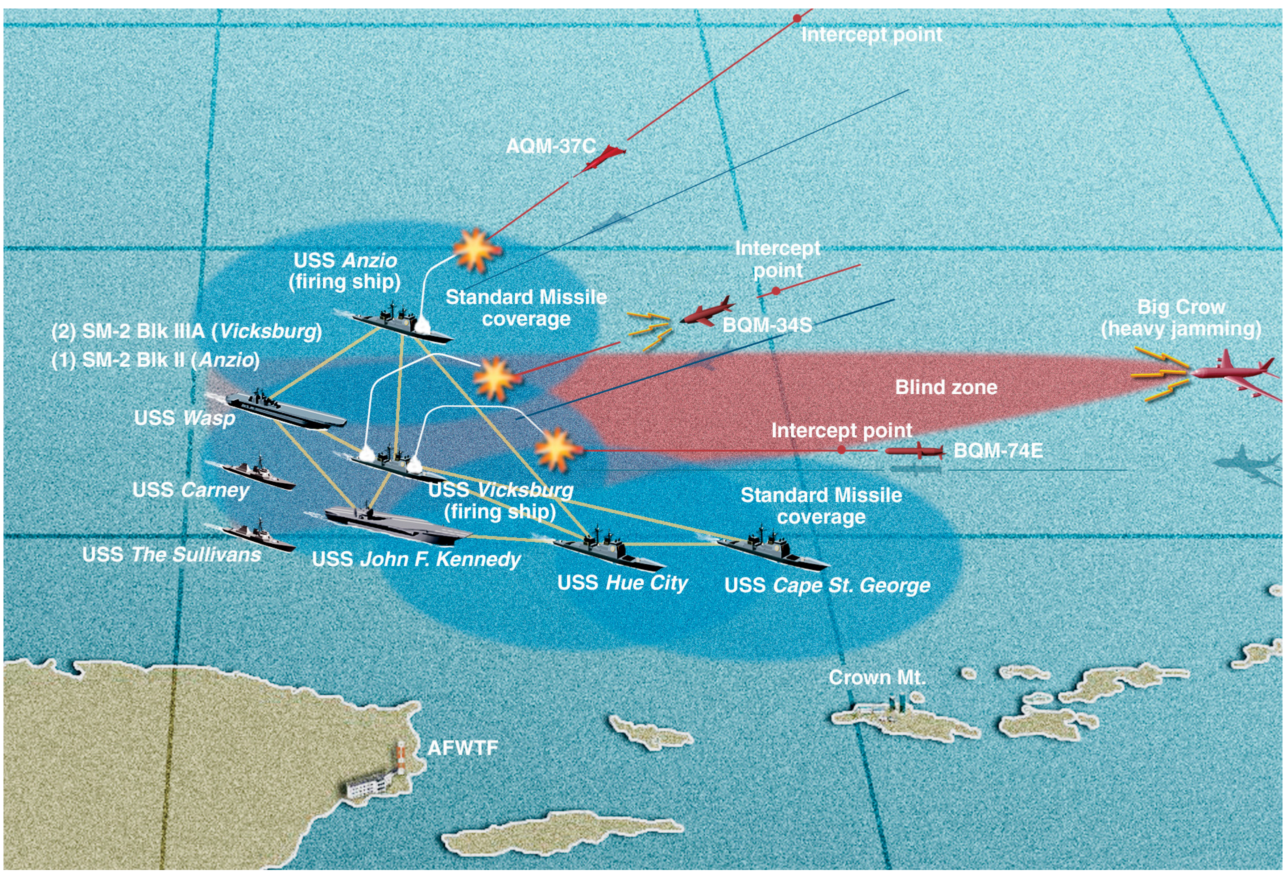

Figure 8. The TECHEVAL scenario proved that guided missile cruisers and destroyers could protect the carrier. It demonstrated retention of AWS/CEC capability in a stand-off jammer environment and retention of AWS/CEC performance in a chaff/jamming environment, in addition to demonstrating that high-altitude debris had no effect on CEC operation.

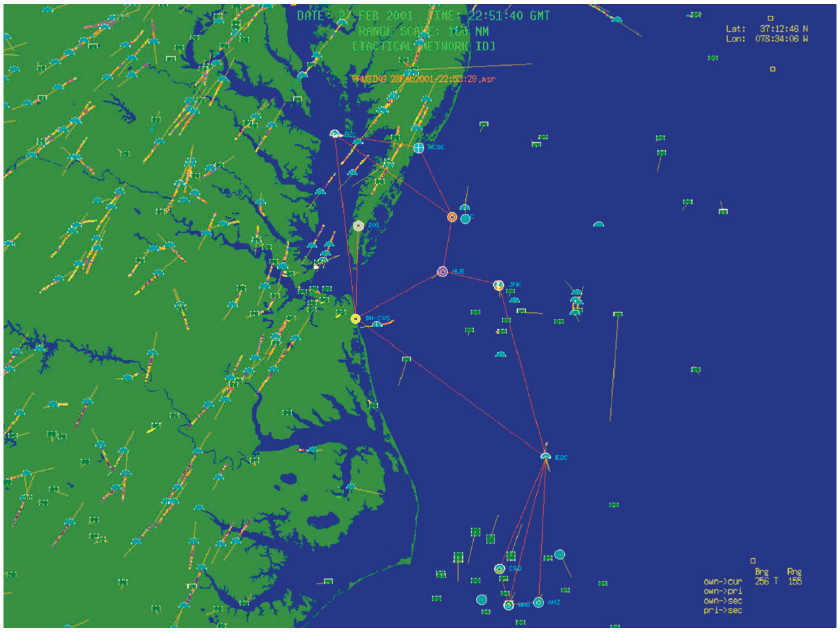

Figure 9. TECHEVAL 11 node net, 27 February 2001 (800–1000 tracks, 700 X 800 nm coverage, 4-h stress test period).

and missile types, and naval ships and aircraft. As a result of this testing, COTF found the surface CEC system, AN/USG-2(V), in a Baseline 2.0 configuration to be operationally effective and operationally suitable.[3] This unconditional acceptance is unusual for systems of this size and complexity.

During this same time frame, CEC was installed on an E-2C aircraft to further the developmental testing of the contributions of the airborne sensors to the sensor network. Figure 10 shows that the airborne sensors not only provide extended radar horizon coverage, but can also contribute significantly to the continuity of tracks held in common with the surface radars. Testing with the E-2C and modeling and simulation of future airborne sensor capabilities have shown that the E-2C will be a crucial component of the Navy's extended-range anti-air warfare capability. CEC testing with the E-2C will continue in the follow-on test and evaluation events planned over the next couple of years.

JOINT APPLICATIONS

Although CEC was originally conceived and designed primarily to support Navy sensor netting with integrated fire control, the concept, if not the system, can be the basis for a Joint sensor netting application. Lessons learned from CEC are consistent with many of the conclusions of the Joint Composite Tracking Network (JCTN) Study sponsored by the Joint Theater Air and Missile Defense Office (JTAMDO).[4] This study proposed requirements for a Joint system that would provide sensor networking and integrated fire control capabilities for theater-wide operations in the future. The study concluded that CEC could provide the basis for future JCTN development.

The Marine Corps AN/TPS-59 radar was the first land-based tactical air defense radar to be integrated into the CEC network. Using CEC information, the Marine Corps has demonstrated the ability to fire the Homing All the Way Killer Missile, Advanced Medium-Range Air-to-Air Missile, and Avenger Missile at threat cruise missiles and is currently pursuing the acquisition of CEC equipment for use with their mobile air defense systems.

A number of advanced demonstrations have been pursued that have performed trial integrations of Joint air defense sensors in the CEC network. These live demonstrations, data collections, and simulations have involved the primary air defense sensors associated with Patriot, Theater High-Altitude Area Defense,

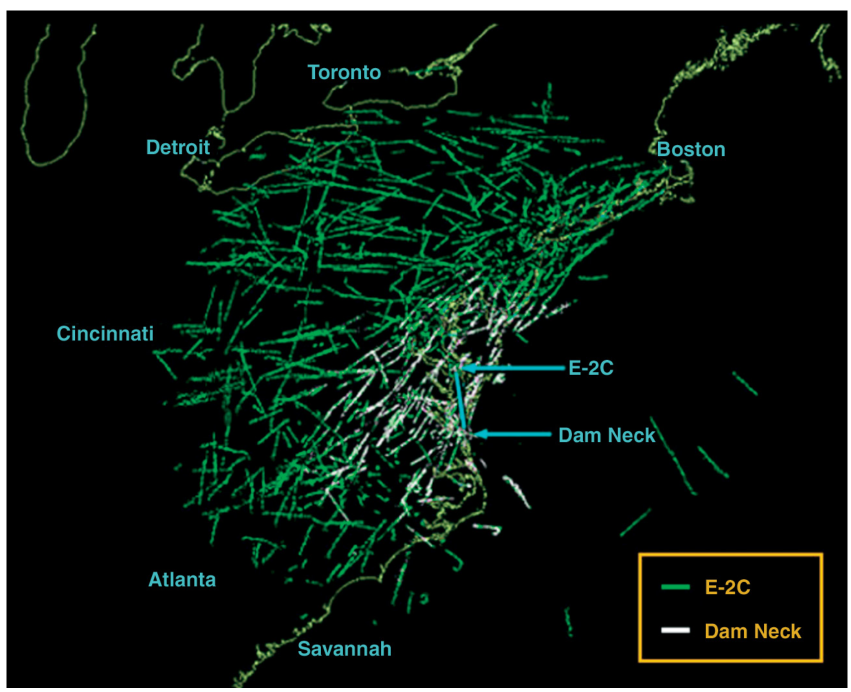

Figure 10. CEC/E-2C composite picture.

and Airborne Warning and Control System. The only way a Joint force will be truly effective and interoperable in a stressing tactical environment is through Joint sensor netting that encompasses all primary air defense sensors. Conversely, independent modeling and simulation sponsored by JTAMDO has shown that primary air defense sensors brought into a theater that are not integrated into the sensor netting will only degrade the consistency and clarity of the Joint tactical air picture that is provided over the data links.[5]

ADVANCED SENSOR NETTING

CEC currently processes and distributes radar and IFF data. Although this enables the creation of a very robust tactical air picture, ID of many of the threat aircraft must be inferred by the knowledge that they are not known friends and that their behavior (flight profile) is suspicious. It would be advantageous to be able to incorporate other types of sensors and sensor parametric or signal information, which would support the detection and classification (if not the outright ID) of the threat aircraft. One class of sensors that would fit this need is precision electronic support measures (ESM) systems.

For shipboard application, the accuracy of the AN/SLQ-32 system will not support real-time high-confidence correlation of the detected threat radar emissions with the radar measurements on a sensor network; however, analysis has shown that the projected airborne and ship ESM precision described in the AN/SLY-2 Advanced Integrated Electronic Warfare System requirements would meet sensor netting quality constraints. Sensor netting the ESM bearing lines and parametric data could greatly increase the effectiveness of these data and their correlation to the tactical picture, thereby enhancing the ability of the force to identify hostile aircraft and missiles at much greater ranges.

To take advantage of the full power of sensor netting, CEC must be expanded to process and distribute more of the information available in the radar waveform. Future high-resolution radars will have the ability to measure the dimensions of an aircraft's major structural elements. The effectiveness of this capability to identify the type of aircraft being radiated depends on the aspect angle of the radar location to the aircraft orientation. Sensor netting this information and combining it with information from similar sensors on other units at different aspect angles will greatly increase the probability of correctly identifying the type of aircraft.[6] Figure 11 shows how the probability of correctly identifying the aircraft type depends on the number of aspect angles.

The value that sensor netting can bring to this process is immediately evident. There are similar examples with regard to the use of electro-optical and infrared sensors where netting of precision sensors can have a force-multiplying effect.

It is also advantageous to provide the CEC picture to other collection platforms where communications intelligence and signal intelligence can be correlated

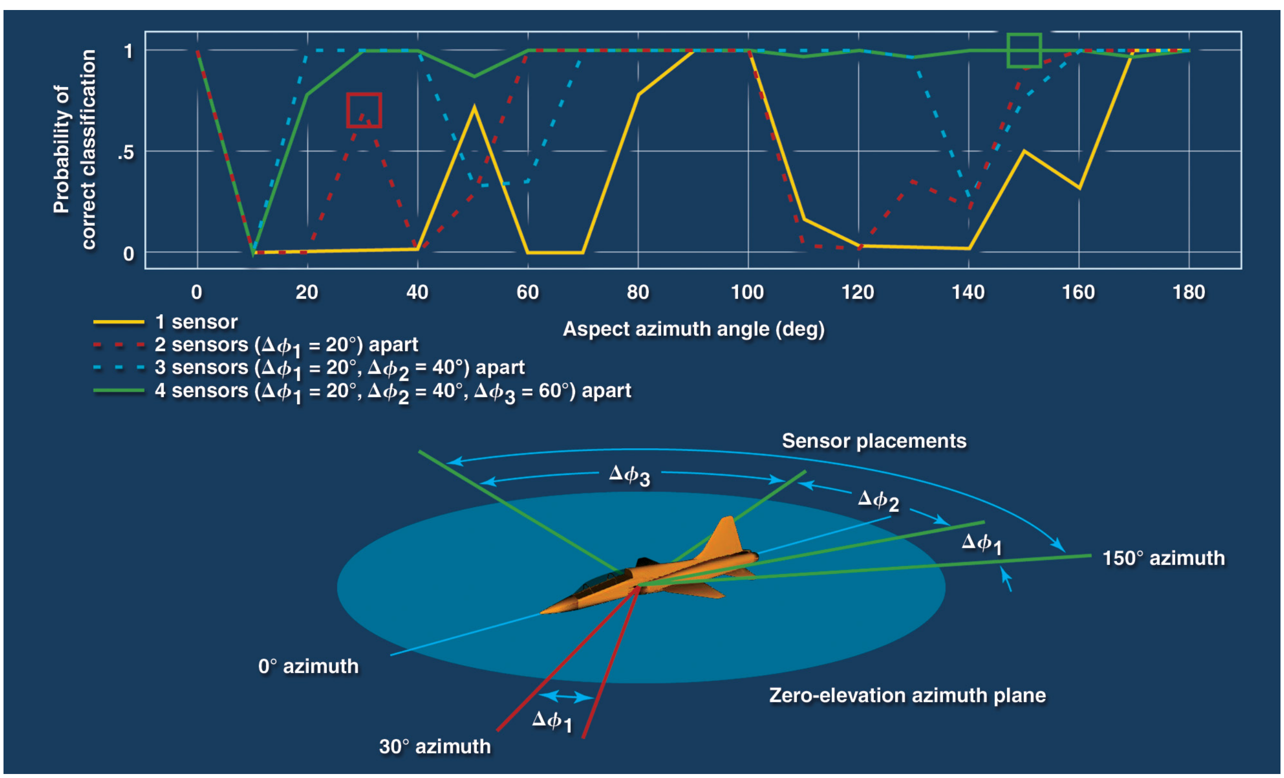

Figure 11. Enabling target classification with multi-aspect high-resolution radar profiles.

to the high-fidelity CEC tactical air picture. This could result in the high-confidence ID of threat aircraft by other systems. All of the aforementioned approaches are being pursued by the Laboratory in the hope of being able to create a sensor netting capability that will enable the ID and engagement of hostile aircraft at extended ranges before they become immediate threats to U.S. forces.

If the full potential of sensor netting is to be realized in CEC, two challenges must be met. The first is that CEC must be made extensible to multiple levels of communication service; e.g., via satellite for long-range relay and via lower-quality data-link connectivity like that used for remote sensing platforms. The major technical hurdle is to develop algorithms that will enable the incorporation of sensor information from lower-quality data sources and links into the sensor network without corrupting the quality of the composite air track and ID picture. Data fusion algorithms must be proven through prototyping and realistic testing to determine the real effect they have on sensor netting and composite tactical air picture quality.

The second challenge, mentioned in the Introduction, is that the sensors, combat direction systems, and weapon systems being conceived for future ship-, aircraft-, and land-based air defense systems should be designed assuming sensor netting as a core capability rather than something that is added as an afterthought. Air surveillance sensors that are designed to be used cooperatively in a sensor net will be much more powerful collectively and in concert than just the sum of their tracks. Weapon systems that can be cued or completely directed with remote sensor information will have much greater lethality and reach against the threat.

Finally, combat direction systems that optimize the use of the information available through sensor netting rather than reliance mainly on local sensors will be much more capable of identifying threat aircraft and missiles and engaging them at extended ranges before they become a self-defense concern.

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ACKNOWLEDGMENTS: The CEC concept was conceived by APL in the early 1970s. Serving as the Technical Advisor to the Aegis Program Manager, the Laboratory developed requirements and performed laboratory and at-sea critical experiments that led to the design of CEC. A multidisciplined team of scientists, engineers, programmers, and operationally experienced personnel defined and led the initial proof-of-concept experiments that demonstrated the value of sensor netting with integrated fire control and proved that the capability could be achieved. The many APL staff members that have dedicated the last decade or more to bringing this capability to the Fleet are too numerous to mention individually, but CEC would not have become a reality without their perseverance. This article is dedicated to them. The CEC Program, established in 1987, was managed by what became the Navy Program Executive Officer for Theater Combatant Systems (PEO(TSC)) in the CEC Program Office, PMS-465. Under their direction, the Laboratory worked collaboratively with the Naval Sea Systems Command's Dahlgren, Crane, Port Hueneme, and Corona divisions as well as with Raytheon Systems Company, Lockheed Martin Corporation, Grumman Corporation, and others in developing and testing the operational CEC aboard several ship classes and the E-2C. The combined efforts of these organizations, in conjunction with the PEO(TSC) Interoperability Task Force and the superb support of the test ranges and land-based test sites contributed to the complex task of equipping and testing two battle groups in a complex, operationally representative environment for TECHEVAL and OPEVAL. Thousands of individuals throughout these laboratories, commands, and companies helped make the CEC OPEVAL a success.

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