The Cooperative Engagement Capability*

A revolutionary approach to air defense has been extensively evaluated recently. The approach is a new Cooperative Engagement Capability (CEC) that allows combat systems to share unfiltered sensor measurements data associated with tracks with rapid timing and precision to enable the battlegroup units to operate as one. The CEC system and the program for Fleet introduction are described. Further, the results of recent testing as well as new CEC concepts applied to multiwarfare, joint-services, and Allied operations are discussed. The role of the Applied Physics Laboratory from conception through our current leadership efforts is also highlighted.

INTRODUCTION

Operation in the littoral theater is a principal Navy 1990s scenario with complexities never considered in the Cold War era. For theater air defense, the complexities include the natural environment and its effects on sensor range. For example, desensitization by clutter from propagation ducting and rough terrain, as well as blockage by coastal mountains and cliffs, reduces the time available for a defensive system to react. In addition, commercial, nonbelligerent aircraft and ships compound the already difficult problem of sorting friends, neutrals, and hostiles during major Allied operations involving many other ships and aircraft (Fig. 1). Introduced into this backdrop are potential enemy systems, such as sophisticated and mobile electronic warfare systems; new-generation, sea-skimming cruise missiles; target observables reduction technologies; and theater ballistic missiles, along with tactics such as aircraft and ships disguised and lurking among commercial traffic.

To successfully perform its intended missions of air control and power projection ashore, the Navy must defend itself and its assets ashore with combatants dispersed over thousands of square miles. Each combatant will possess one or several sensors totaling, perhaps, more than 50 among Allied theater forces, and each sensor will observe a somewhat different view of the situation because of its unique characteristics and vantage point. Amidst this disparity in knowledge among coordinating units are efforts to correlate target tracks and identification data via conventional command/control systems and to coordinate 20 to 30 missile launchers and a comparable number of interceptor aircraft.

Coalescing this collection of equipment into a single war-fighting entity requires a system that will complement both new-generation and older air defense systems by sharing sensor, decision, and engagement data among combatant units, yet without compromising the timeliness, volume, and accuracy of the data. The system must create an identical picture at each unit of sufficient quality to be treated as local data for engagements, even though the data may have arrived from 30 to 40 mi. away. If a common, detailed database is available to provide a shared air picture as well as the ability to engage targets that may not be seen locally, a new level of capability may be attained.

This ability is precisely what the Cooperative Engagement Capability (CEC) provides for a network of combatants. Recent tests demonstrated that from older, short-range systems such as NATO Sea Sparrow through the latest Aegis baselines, CEC can provide greater defensive capabilities and even provide new types of capabilities to a battle force. However, CEC does not obviate the need for advances in sensors, fire control, and interceptors. Rather, CEC allows the

*Individual authorship is not provided in recognition of the many APL staff members who have contributed in a substantial way to this program.

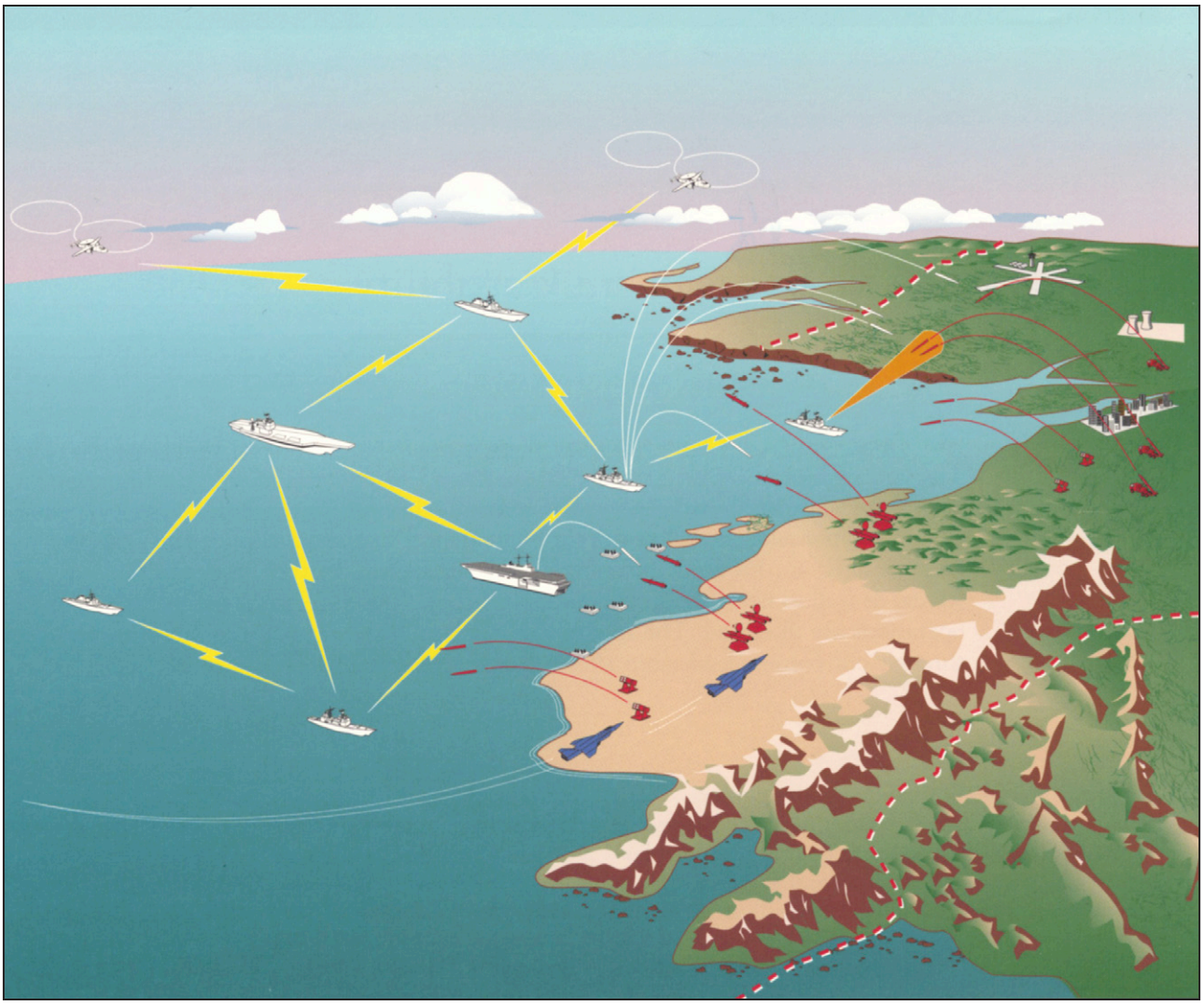

Figure 1. The littoral battle environment. Some of the complexities of the environment include friendly, hostile, and neutral forces; advanced cruise missile, electronic warfare, and tactical ballistic missile threats; and a multitude of Allied combatants with multiple sensors and weapons that must be closely coordinated.

benefits of the newest systems to be shared with older units and provides for greater total capability despite the decline in the number of U.S. and Allied forces.

CEC DESCRIPTION

The CEC is based on the approach of taking full advantage of the diversities provided by each combatant at a different location with different sensor and weapons frequencies and features. This approach requires sharing measurements from every sensor (unfiltered range, bearing, elevation, and, if available, Doppler updates) among all units while retaining the critical data characteristics of accuracy and timeliness. For effective use, the data must be integrated into each unit's combat system so that it can use the data as if it were generated onboard that unit. Thus, the battle force of units networked in this way can operate as a single, distributed, theater defensive system.

Principles of Operation

Composite Tracking

Figure 2 illustrates the principal functions of CEC. Specifically, Fig. 2a indicates sharing of radar measurement data that are independently processed at each unit into composite tracks (formed by appropriate statistical combining of inputs from all available sensors) with input data appropriately weighted by the measurement accuracy of each sensor input. Thus, if any unit's onboard radar fails to receive updates for a time, the

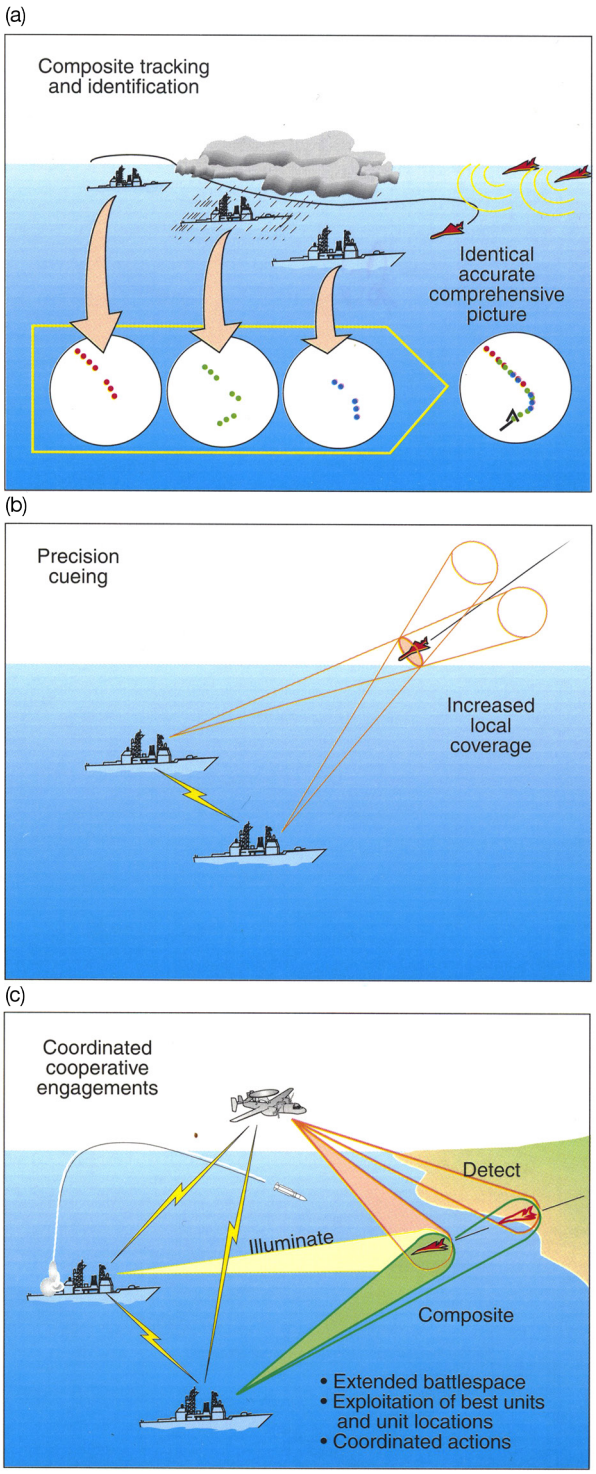

Figure 2. The principal CEC functions include composite tracking and identification, precision cueing, and coordinated cooperative engagements.

track is not simply coasted (with the attendant risk of track loss or decorrelation with the tracks of other units reported over tactical command/control data links), but rather it continues because of data availability from other units. This function is performed for radars and for the Mark XII Identification Friend or Foe (IFF) systems with IFF transponder responses as "measurement" inputs to the composite track in process. The composite track function is accompanied by automatic CEC track number commonality, even when tracking is being performed simultaneously at each unit. Also provided is the composite identification doctrine, as input from a console of a selected net control unit (NCU), for all CEC units to implement to jointly decide on a target's classification. Doctrine is logic based on data such as velocity and position relative to borders and airways in addition to direct IFF response measurements and codes.

Precision Cueing

To facilitate maximum sensor coverage on any track, a means of special acquisition cueing is available (Fig. 2b). If a CEC track is formed from remote data but a unit does not locally hold the track with its radars, the combat system can automatically initiate action (a cue) to attempt the start of a local track if the track meets that unit's threat criteria. A CEC cue allows one or several radar dwells (with number and pattern determined by the accuracy of the sensor(s) holding the target). Given that at least one radar with fire control accuracy in the network contributes to the composite track of a target, then cued acquisition by a phased array radar with only a single radar dwell at high power and maximum sensitivity is possible, even if substantial target maneuvering occurs during target acquisition. For a rotating radar, the target may be acquired by a localized sensitivity increase in a single sweep rather than by requiring several radar rotations to transition to track. Studies and tests have shown that the local acquisition range can be greatly extended simply by not requiring the usual transition-to-track thresholds (for detection and false alarm probability control) to be required since the precise target location is known. Retention of radar accuracy within the CEC net is accomplished via a precision sensor-alignment "gridlock" process using the local and remote sensor measurements.

Coordinated, Cooperative Engagements

With the combination of precision gridlock, very low time delay, and very high update rate, a combatant may fire a missile and guide it to intercept a target, even a maneuvering one, using radar data from another CEC unit even if it never acquires the target with its own radars. This capability is known as engagement on remote data, and, with the Navy's Standard Missile-2 (SM-2) series, allows midcourse guidance and pointing of the terminal homing illuminator using offboard data (Fig. 2c). The remote engagement operation is essentially transparent to the combat system operators.

Engagements can be coordinated, whether conventional or cooperative, via real-time knowledge of the detailed status of every missile engagement within the CEC network. Moreover, a coordination doctrine may be activated by the designated NCU for automated engagement recommendations at each unit based on force-level engagement calculations.

CEC System Design

Processing and Data Transfer Elements

To provide such a data-sharing capability requires a design that allows each radar and weapon control subsystem to receive remote data of the same quality and timing over its interface as the data it normally receives from its onboard subsystems. This requirement necessitated introduction of a new processing element, the Cooperative Engagement Processor (CEP), and a new data transfer element, the Data Distribution System (DDS) (Fig. 3). Because each CEP must process the data provided both locally and from all units in the CEC network, it must possess processing capacity and throughput comparable to the combat systems of an entire battle force. This capability is achieved by a bused architecture of 30 commercial microprocessors (presently Motorola 68040) with a unique message-passing architecture in a reinforced cabinet. Figure 4 is a photograph of the CEC equipment onboard the USS *Cape St. George*. Each processor performs at least one of the processing subfunctions such as track filtering, track divergence and convergence testing, gridlock, sensor interfacing, cooperative engagement support, and DDS interfacing. The CEP is generally interfaced directly with the onboard sensors to ensure that the data are transferred within a stringent time budget. The CEP interfaces with the onboard command and control subsystem to ensure coordination of activity with local combat system operations. Finally, the CEP is linked with the weapons subsystem computers to ensure timely availability of precise fire control data to guide cooperative engagements.

The DDS must ensure highly reliable transfer of data also within a stringent time budget and without constraining the rate or capacity of reported data within the CEC network. Essentially, the DDS must transfer data so that it is available to a receiving weapon system with attributes that are identical to the data that system receives from its own onboard sensors and weapons. Thus, the DDS timeliness, capacity, and reliability of data received from miles away must be comparable with that from an interface to a weapon computer from a local sensor computer only a few feet away. The resulting DDS performance is several orders of magnitude more capable in nearly every category relative to conventional tactical data links, i.e., in capacity, cycle time, update rate, message error rate, availability in jamming, and margin against propagation fading. This performance requires a high effective radiated power, large spread-spectrum bandwidth, and precise timing. To achieve this performance reliably requires a phased array antenna for each DDS terminal, used for both transmission and reception of data at different times, and a high-power traveling wave tube transmitter. Because the arrays allow a DDS to transfer or receive data from only one other unit at a time within mutually pointing antenna beams, a unique, new, distributed net architecture with a high degree of automatic operation was required. Figure 5 shows the current ship phased array antenna on the USS *Cape St. George*.

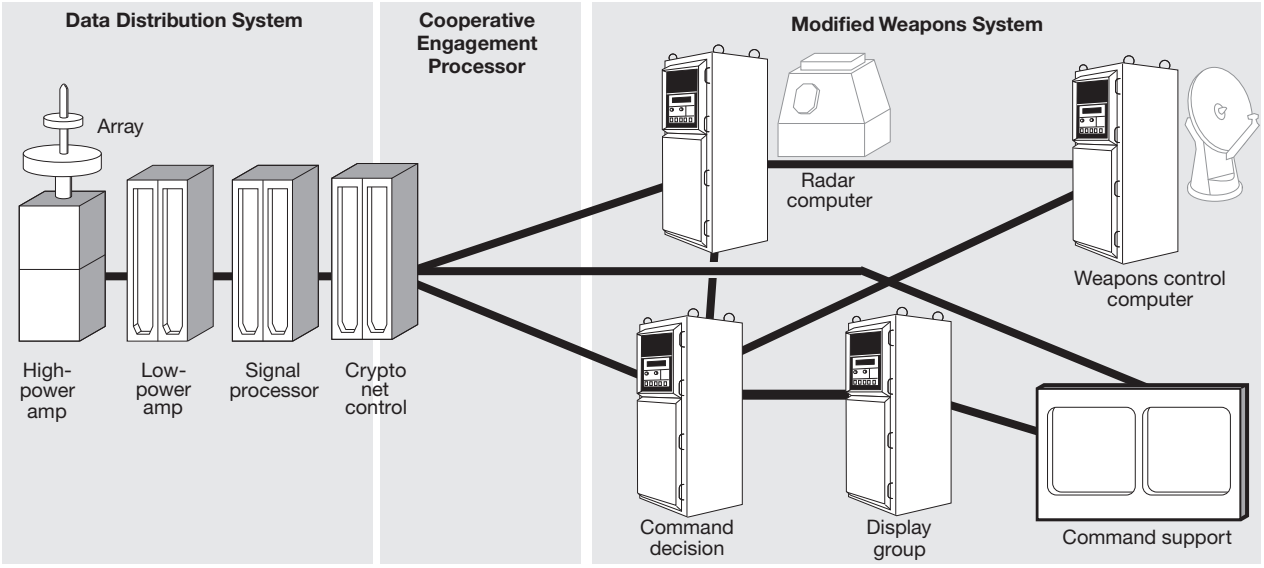

Figure 3. CEC functional allocation. The DDS and CEP are shown interfaced to a representative combat system.

Figure 4. CEC equipment installed on the USS *Cape St. George*. Shown are the cabinets that house the CEC electronics.

Figure 5. The DDS phased array antenna on the *USS Cape St. George.* The array is a 44-in.-dia. by 14-in.-high cylinder with about 1,000 array elements. It is capable of steering in both azimuth and elevation. The large structure underneath the array is an electromagnetic shield between the DDS and LAMPS antennas.

New Net Architecture

In essence, an operator at the designated NCU enters the "net start" command, and that DDS begins searching for other DDSs in a manner similar to IFF systems by sweeping its array antenna beam and transmitting interrogations. Synchronously, other units sweep their array beams in a reciprocal fashion to receive interrogations, respond to them, and begin to assist in the interrogation process by locating other units, for example, beyond the horizon of the NCU. By the end of the net start process, all units within direct or indirect line-of-sight have knowledge of the locations of all other units and are connected with line-ofsight units. An interim, common schedule algorithm is exercised independently by all units by which they send microwave "bursts" of data parallel to different designated units at precise times with precise, encrypted, spread-spectrum sequences. Because of the phased arrays, each unit tracks the other units to which it is in direct communication, and the sharing of this position data allows the CEP to begin the gridlock alignment process. The DDSs simultaneously switch to identical (but individually generated) schedules, indicating which units communicate with each other in any multimillisecond time frame.

The precision timing required for the spread-spectrum waveform, data transfer, and identical independent processing by each unit is provided by a cesium clock embedded into the CEC equipment. The clocks are synchronized across the CEC net to within microseconds of accuracy via DDS time synchronization processes. If a unit loses connectivity with another unit, then, based on sharing this knowledge, all other DDSs in the net revise their schedules identically and route data around that broken connectivity path. New connections and new units may be added to the net with automatic netwide adjustment. All units can automatically provide relaying as needed. Therefore, no operator interaction is required except to change the system state (e.g., on/off).

Integrating CEC into Combat Systems

Modifications to each combat system integrated with CEC are required to allow utilization of remote radar and engagement data in a manner similar to that of data generated onboard. In principle, radar and IFF measurements must be sent to the CEP with little time delay once at least tentative track is achieved for a new target. If a remote unit detects a new target, then that unit's CEP receives the data and transmits it to all other CEPs via the DDS. The local CEP gridlocks (aligns remote data into local coordinates) and inserts the new data into the tracking process. These data are then made available to the local radar computer for scheduling of cued acquisition cue dwells (generally with waveform selection for optimum acquisition), thereby providing for enhanced local detection of the target. This cueing occurs if the local radar has sufficient time and energy available and the target track satisfies tactical interest criteria set at the local combat system.

Design improvements have been made for some radar systems as part of the CEC integration process to ensure low false track rate on the net and yet high sensitivity for cueing. Generation of false tracks, e.g., due to clutter, at a rate tolerated on a single unit is often too high for a network of units, so further processing is provided in the CEP. Net control status, doctrine, remote engagement status, and local radar activity requests are generally communicated to the local command and decision element of a weapon system. Cooperative engagements can be prosecuted by providing remote fire control radar data at high update rate to the weapons control subsystem. CEC composite track data are available to the tactical data links, Links 11 and 16, via the command and decision element.

The AEGIS and LHA Class Combat Systems

Diagrams of two types of combat systems integrated with CEC are shown in Fig. 6. The Aegis combat system integration (Fig. 6a) is representative of current-generation integrations with direct interfaces to the subsystem elements. Direct interfacing to the Aegis weapon control system will be required at a later phase and is already accomplished for the other combat systems. The LHA class amphibious assault ship (Fig. 6b) will be integrated with CEC in the late 1990s and will feature the Advanced Combat Direction System (ACDS) Block 1 and Ship Self-Defense System (SSDS) in a bus or local area network medium. APL is the Technical Direction Agent (TDA) for SSDS.

The adaptation software for CEC and combat system elements is always developed to allow custom integration with each type of combat system for maximum netwide cooperation and maximum benefit to the local system. This work is performed in collaboration between CEC and combat system engineers. Because of the differences in combat systems, i.e.,

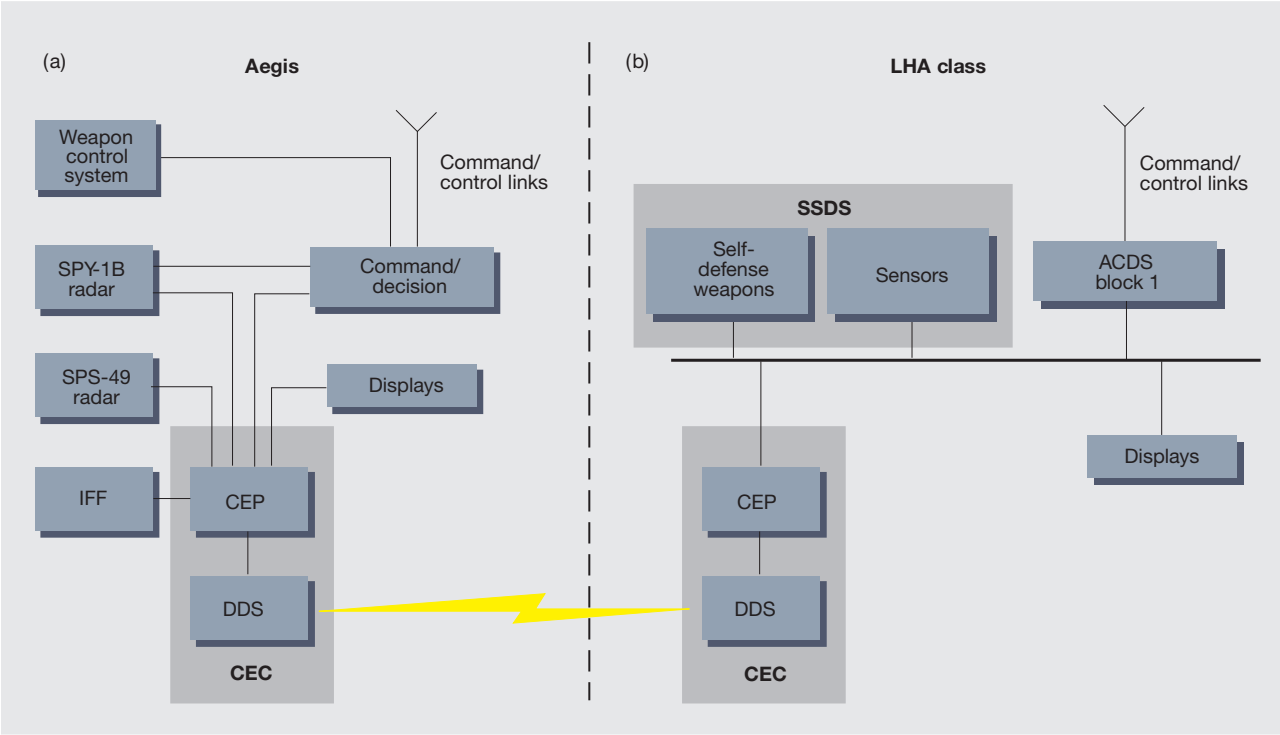

Figure 6. CEC integration diagrams for two types of combat systems: (a) the current Aegis/CEC integration and (b) a concept for the future LHA integration upgrade including APL-led CEC and SSDS systems.

between the Aegis phased array multifunction radar and Standard Missile long-range defense capability, and the LHA system advanced self-defense and command control in support of amphibious operations, the interaction of the combat systems with CEC is different in the areas of radar and weapons cooperation. Common to both systems, however, is full availability of CEC data from all net members for independent construction of an identical, detailed, and composite track and identification picture along with real-time detailed status of all engagements. The types of combat systems to which CEC is presently integrated, or will be integrated within several years, include Aegis cruisers and destroyers, Tartar New Threat Upgrade destroyers, aircraft carriers and large-deck amphibious ships, and the E-2C Airborne Early Warning (AEW) carrier-based aircraft.

Common Genealogy Software

A new and important concept developed by APL that is being applied to Navy combat systems is the use of "common genealogy" software that can be used with little refinement for different implementations, thus significantly reducing costs for development and support. More than 50% of SSDS software is common or nearly common with CEC. Most of this common software was originally developed at APL. Examples of common genealogy software are tracking interfaces with onboard radars, track filtering, onboard and remote cueing control, and display.

Although CEC is highly interactive with the subsystems to which it is interfaced, the interactions are automatic so that CEC operation with the combat systems is essentially transparent. No new operator is required onboard any unit as a result of CEC, and recent battlegroup evaluations have determined that the degree of CEC automation provided to the combat system reduces the workload on existing operators at their stations. Essentially all that is required to initiate CEC is for the designated NCU to select "net start" from the CEC display window menu and "net shutdown" to curtail operations. If desired, net control, identification, and engagement doctrine may also be entered by the NCU and promulgated throughout the CEC net for identical implementation by all net units, allowing further performance tailoring. The other CEC net members may initiate "net entry" or "terminal signoff" to enter or leave an already established net, respectively. The CEC display is available for selection at most operator stations so that composite data can be reviewed in detail, i.e., which sensors are contributing, track histories, and applicable doctrine.

APL'S ROLE IN THE CEC PROGRAM

The CEC concept was conceived by APL in the early 1970s. Requirements development and critical experiments were performed primarily by APL as TDA for the Navy air defense coordination exploratory development program, which was originally called Battle Group Anti-Air Warfare (AAW) Coordination. The first critical at-sea experiment with a system prototype occurred in 1990. The CEC became a Navy acquisition program in 1992, and in May 1995, it passed an important test-phase milestone. Congress and the DoD have accelerated the program as a result of these successful tests and have directed that integration with Army and Air Force systems also be jointly pursued. Figure 7 illustrates the key events of the CEC program. Initial trial deployment occurred in the Mediterranean from October 1994 through March 1995 with a battle group of the Sixth Fleet. Initial operational capability with all test limitations removed is scheduled for 1996. By 1999, Navy ships from all major classes as well as the E-2C AEW carrier aircraft will be outfitted with CEC with an aggressive schedule for completion within the next 10 years.

The CEC program is managed within the Navy Program Executive Office for Theater Air Defense. The Laboratory, as the TDA, has worked in partnership with the Navy and the prime contractor Raytheon/E-Systems/ECI Division to develop specifications and the prototype system. APL has continued to lead in the definition of interfaces and modifications to the combat systems for integration with CEC. This task has involved collaboration with major combat system companies including Lockheed Martin, Hughes Aircraft, ITT Gilfillan, and Northrup/Grumman Corp. As Test Conductor, the Laboratory has led testing from the individual CEC element level (e.g., software modules) through large-scale, at-sea Fleet tests. This system engineering process has completed several cycles, or evolutions, culminating in the development test in 1994, which was the last major test before CEC Initial Operational Capability certification in 1996. This 1994 test is described further in the next section. Figure 8 summarizes APL's role in CEC.

RECENT TESTS

The CEC development test evolution in 1994 was one of the most complex in Navy history. For the first time, the capital ships of a carrier battle group were to be the collective "article under test"; never before had the Navy dedicated an entire battlegroup for testing. Two types of test evaluations occurred in the series: development testing (DT-IIA), in which design and

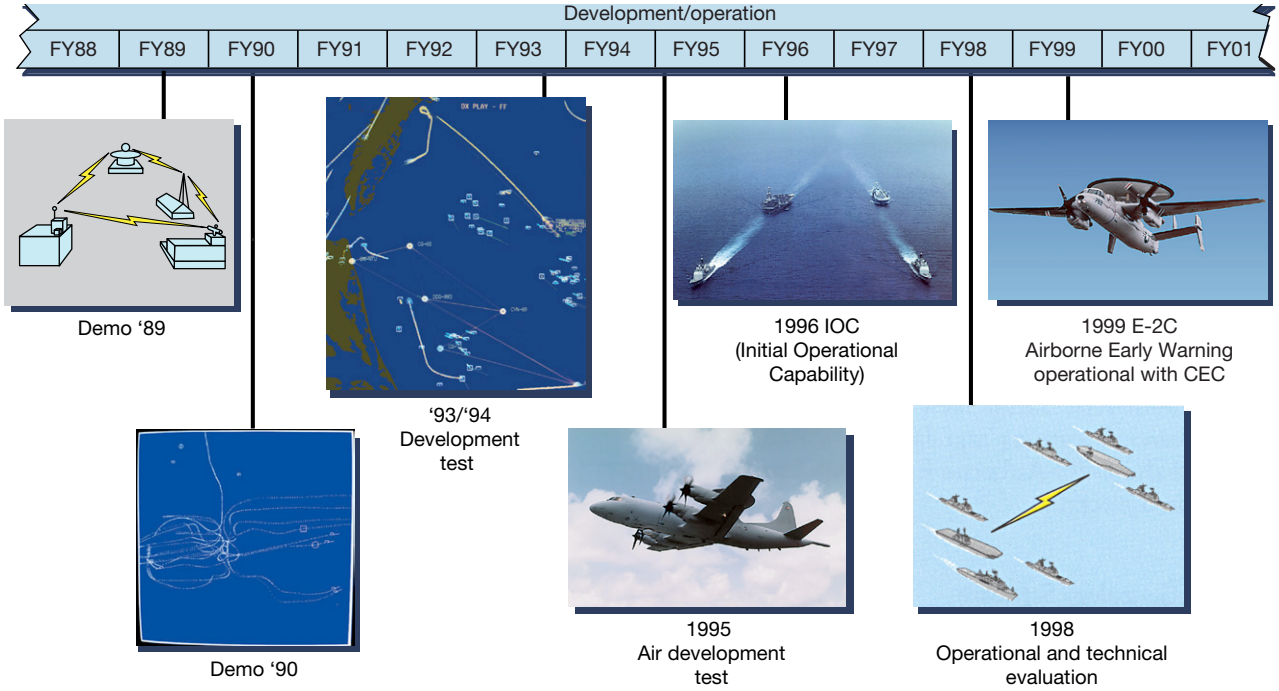

Figure 7. Summary of CEC program major events from early concept validation to full production.

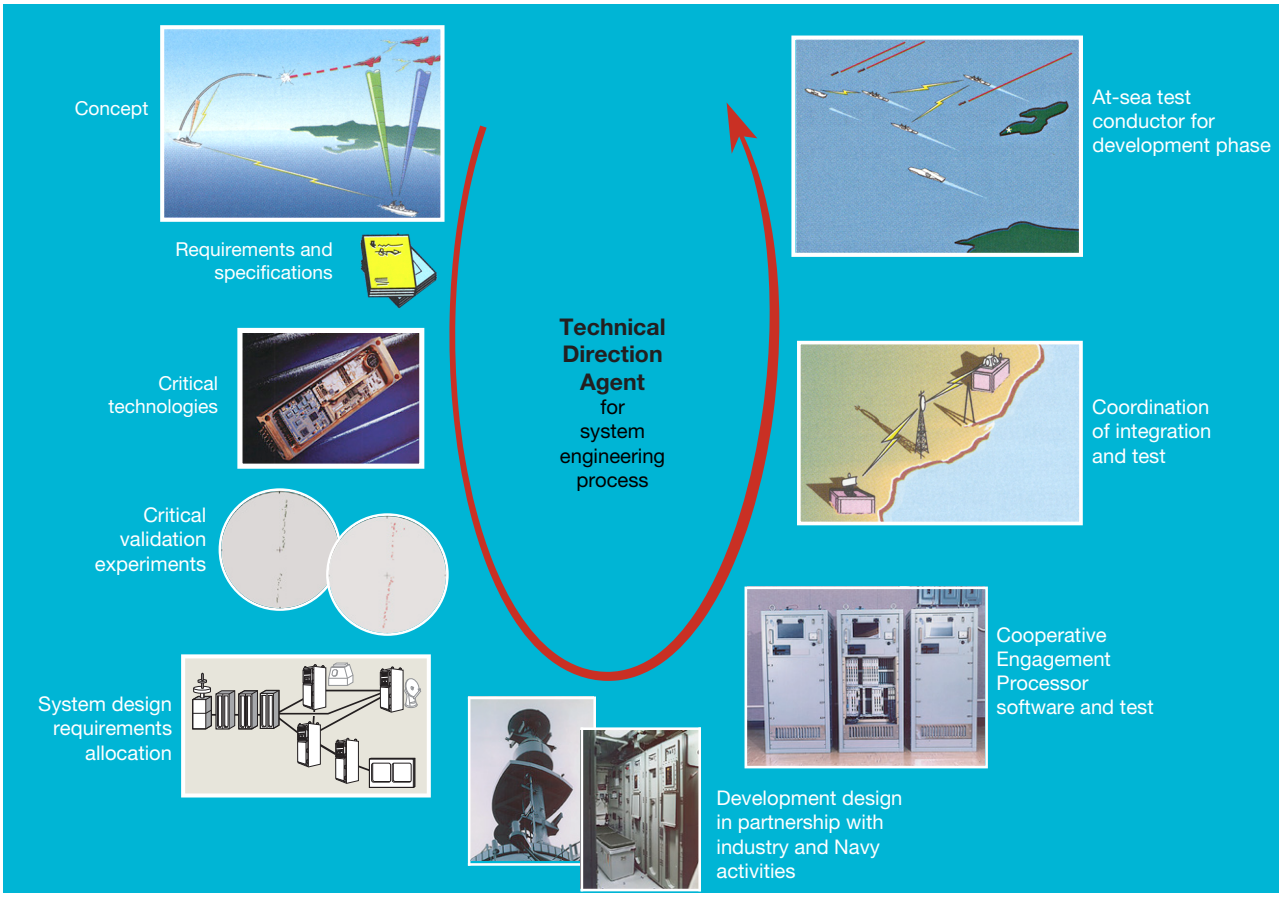

Figure 8. APL's role in CEC development. The "horseshoe" indicates the system engineering process beginning with a need and concept and progressing into more detailed design iterations. Testing commences at this lowest level of detail (i.e., circuit card and computer code module) and progresses into a larger scale culminating with total system test. APL conceived and developed the concepts in response to an assessed threat; led development of critical technologies, experiments, and system engineering specifications; worked with industry to design and integrate subsystems; and led the conduct of interface tests through formal development tests.

performance were assessed, and operational testing (OT-1), in which Fleet operational performance was evaluated.

Development Testing

Objectives for the development testing were as follows:

1. Demonstrate the ability of each unit to contribute to and independently develop an identical, detailed, composite track and identification picture from both local and remote radar and IFF measurements for an improvement in situation awareness.
2. Prove that CEC data are sufficiently accurate and fresh to provide for coordinated prosecution of precision-cued and cooperative engagements to improve individual system performance.
3. Demonstrate these capabilities in projected, next-generation cruise missile and electronic warfare threat environments to validate a significant improvement in Fleet defense.

The test period was phased beginning with initial testing of the USS *Kidd*, a New Threat Upgrade Tartar destroyer, in September 1993. The destroyer was tested offshore, communicating with a similar land-based system at the Fleet Combat Direction Support Site near Norfolk, Virginia. By April 1994, three additional ships of the USS *Dwight D. Eisenhower* Nuclear-Powered Aircraft Carrier (CVN) battle group had been integrated with CEC: the nuclear carrier itself and two Aegis cruisers, USS *Anzio* and USS *Cape St. George*. In addition, Congress had directed that a large amphibious ship be equipped with CEC to demonstrate self-defense system cueing in anticipation of the introduction of SSDS; USS *Wasp* was selected and was operating with CEC by April. These five ships represented CEC integration with four different types of combat systems, as shown in Table 1. A sixth unit, a U.S. Customs Service P-3 aircraft equipped with a variant of the E-2C radar and IFF, was also outfitted with CEC. Although CEC was not yet integrated with the P-3 sensors at that time, the aircraft provided DDS air relay test support during this period.

Development/Operational Testing

Virginia Capes Testing

Underway periods for all five ships and the P-3 in the Virginia Capes (VACAPES) region near Norfolk during early 1994 demonstrated the principal nonengagement CEC capabilities. Cooperative engagements themselves were demonstrated at the Atlantic Fleet Weapons Test Facility near Puerto Rico in June 1994. VACAPES test accomplishments included the following:

1. Verification that all CEC units independently construct an identical composite track and identification picture. The tracking was performed in the dense, complex eastern U.S. air traffic corridor with the addition of substantial military aircraft operations from the carriers and large military bases nearby. Severe electronic countermeasures (ECM) against the radars, including deceptive radar jamming, were

Table 1. Systems integrated with CEC.

Units	Sensors	ID	AAW weapon systems
2 Aegis cruisers	SPY-1B (phased array radar)	MK XII (IFF)	SM-2
USS *Anzio*	SPS-49 (UHF long-range search radar)		
USS *Cape St. George*			
Tartar New Threat Upgrade	SPS-48E (S-band search radar)	MK XII	SM-2
destroyer—USS *Kidd*	SPS-49		
	SPG-51 (fire control radar)		
Nuclear aircraft carrier	SPS-48C	MK XII	NATO Sea Sparrow
USS *Dwight D. Eisenhower*			
LHA class amphibious assault	SPS-48E	MK XII	NATO Sea Sparrow
ship—USS *Wasp*	SPS-49		
	TAS (self-defense search radar)		
U.S. Customs Service P-3	APS-138 (airborne surveillance radar)	MK XII	N/A
surveillance aircraft			

Note: N/A indicates aircraft not equipped with AAW weapon systems.

also provided for certain scenarios. The CEC demonstrated its ability to maintain track of ECM-screened targets owing to the diverse locations of contributing CEC units.

2. Verification of the ability to maintain reliable and automated operation of the highly sophisticated DDS network. Network operations were maintained despite severe ECM while retaining the specified propagation fade margin. Network functions that were verified included net start, unit net entry, initial time sync in jamming, directed acquisition of new units, and automatic addition of new connectivity paths and rerouting around lost paths. Also directive, point-to-point, surface-to-air communications with the airborne DDS using its prototype DDS solid-state array antenna were verified for the first time.

Atlantic Fleet Weapons Test Facility Firings

In June 1994, the CEC-equipped battle group transited to the Atlantic Fleet Weapons Test Facility (AFWTF) for air defense missile firings against sea-skimming drones in severe electronic radar countermeasures representing the projected threat. Figure 9a depicts the configuration of the test series. The battle group was deployed against an imaginary shoreline to its east. Drones were launched from Puerto Rico, flown to the east, and then turned to head west and (in most scenarios) drop to sea-skimming altitudes. In some scenarios, ECM aircraft were flown in the east to screen the drones from radars. Two types of cooperative engagements were tested: cued self-defense engagements (Fig. 9b), whereby remote units provided sensor data for precise, automatic radar acquisition by the firing unit, and engagements on remote data (Fig. 9c), where a remote unit automatically provided data of sufficient quality for the firing unit to launch, control during midcourse flight, and perform terminal homing illumination for each SM-2. These tasks were accomplished even though the firing unit may never have been able to detect the drone (e.g., when the ECM was well beyond sensor ECM resistance specifications).

Figure 10 is a display of the CEC composite picture shown in the beginning of one firing scenario. The picture was identical on all CEC units. The color graphics display was produced on engineering workstations installed on the ships for CEC testing. Upgrades of ship consoles to this quality of menu-driven graphics for identical, high-quality pictures are scheduled to begin to be installed on Navy ships concurrent with CEC in 1996. In Fig. 10, the CEC cooperating units are identified with colored circles (labeled LHD-1, CG-68, CG-71, etc.) against a background of geographic features. The composite tracks are shown with track update state history represented as dots, each color-coded to the contributing unit. The symbols for

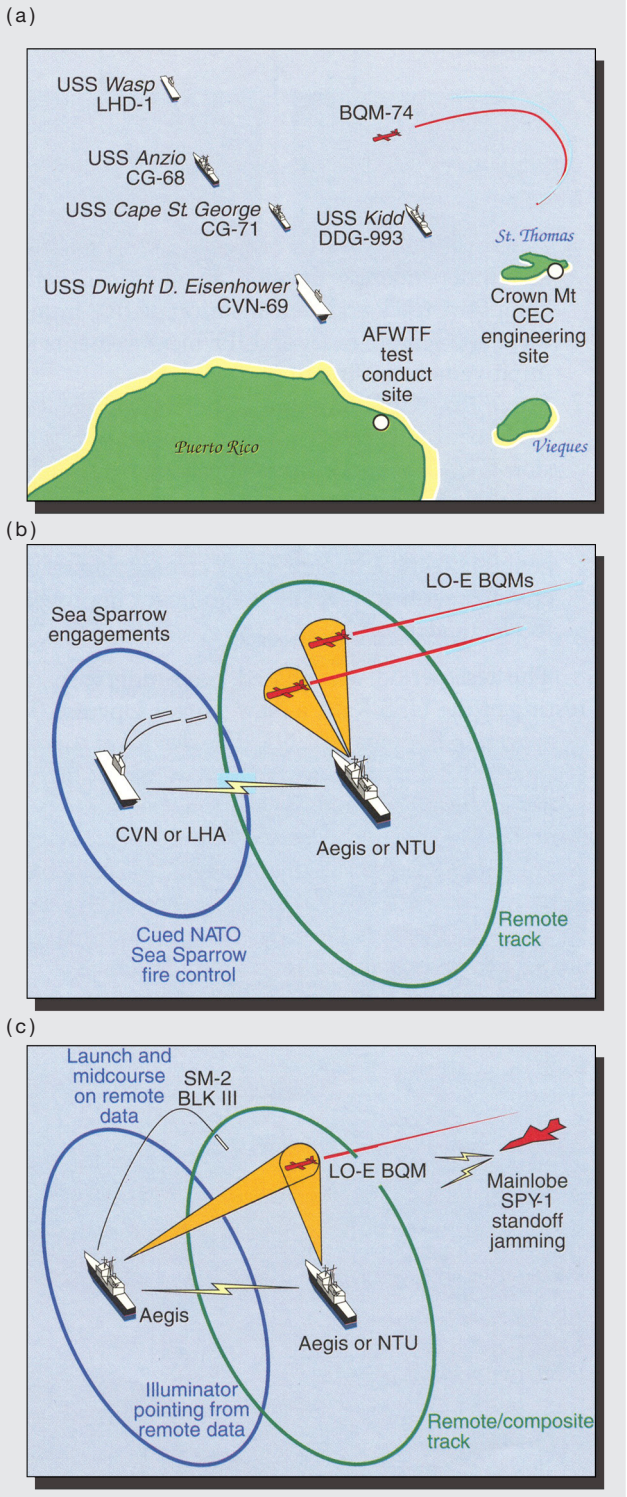

Figure 9. CEC firing events at the AFWTF: (a) the general scenario for the missile firing events with the drone launched from Puerto Rico to begin its inbound run, (b) a cued self-defense engagement, and (c) an engagement on remote data with the source unit supplying fire control radar data to support SM-2 midcourse control and terminal homing illumination by the firing unit.

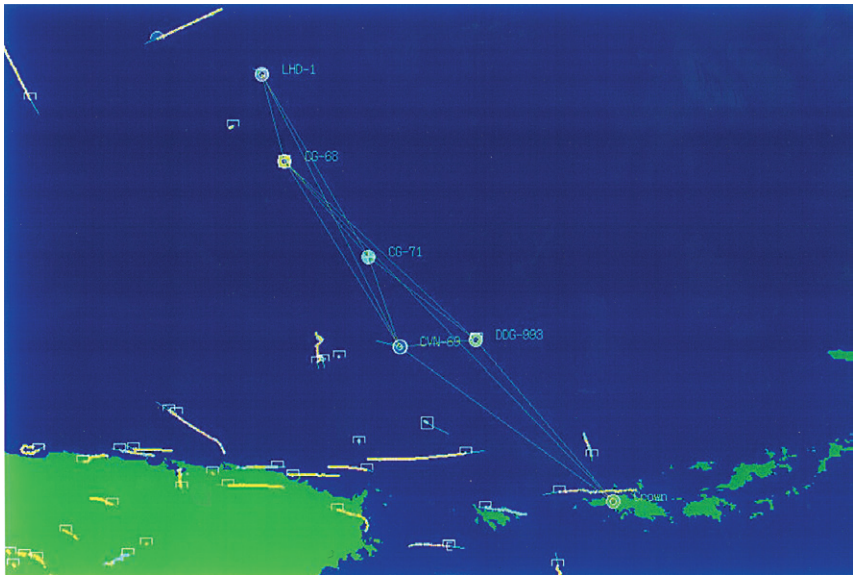

Figure 10. CEC display from the AFWTF. The display shows the composite tracks and their histories, the CEC ships, and the geographic background at the start of a firing scenario event, with the drone indicated by the letter *E* denoting "unknown assumed enemy."

most tracks indicate "unknown assumed friendly" by the upper-half rectangles in accordance with the applicable composite identification doctrine for this scenario. The track with the same symbol but with an *E* embedded identifies the drone as "unknown assumed enemy." It was designated as such by the intended firing unit based on composite data and CEC doctrine just after its launch.

Figure 11 illustrates features of composite tracking at the carrier during one of the test scenarios. In the lower right is a plot of all the sensors in the CEC network (color-coded to their CEC units) contributing measurements to a particular composite track. The three graphs to the left show the composite track filter output (red) for the target and the local (black) and remote (yellow) measurement inputs after gridlock alignment. The composite track states reflect the weighting of input measurements according to accuracy.

A number of important achievements occurred during these June 1994 firing tests:

1. Both types of cooperative engagements, cued self-defense and engagement on remote data, were demonstrated for the first time.
2. The CEC provided the defending self-defense unit with a very early indication of target approaches and remote radar data of sufficient quality to automatically cue the fire control radar for Sea Sparrow intercepts at the earliest possible times and to the range limits of the missile. This efficiency allowed for an additional time margin for more launches if required.
3. The SM-2 engagements on remote data and cueing of the sensors of SM-2 ships proved that substantially increased area defense engagement ranges, to the limit of current missile capability, could be achieved, allowing more opportunities to engage. Figure 12 depicts the CEC track picture just prior to the first-ever engagement on remote data. The Aegis firing unit, CG-68 USS *Anzio*, ordered the target for engagement, and, immediately, the other Aegis unit's SPY-1B radar (USS *Cape St. George*) increased its track update rate on the target to support *Anzio*'s engagement. In this first event, the target was a relatively easy, high-altitude drone, and the firing unit was placed in a nonreporting mode to force the cooperative engagement. Much more difficult scenarios were presented, and CEC successfully allowed the missiles to achieve intercept lethal radius in almost all cases.
4. During the engagements, CEC provided detailed status to all units, indicating the potential for well-informed, real-time coordination of engagements, and anticipating incorporation of automated coordinated engagement recommendations to be provided by the 1996 CEC Fleet introduction. Media coverage of Navy reaction to these events indicated their significance to the nation and the Navy.[1,2]

Battlegroup Operations

Immediately after the AFWTF firings, the CEC-equipped USS *Dwight D. Eisenhower* battlegroup participated in a series of Joint Task Force-95 (JTF-95) exercises in the VACAPES with Army and Air Force units. One important joint-services event was the CEC cueing and composite tracking of a tactical ballistic missile (TBM) target. Figure 13 illustrates the test configuration. CEC data for this event were also made available in real time to separate CEC displays at an Army Patriot unit and at a Marine Corps Hawk battery TPS-59 radar unit to simulate what could be achieved with direct CEC integration with these systems.

Figure 14 shows the composite CEC picture as the test TBM target passes apogee. The composite data and display picture were identical on all CEC units, and the picture was displayed at the land sites. Just after launch, the nearest ship, USS *Anzio*, detected the target with its SPY-1 radar, and the measurement data were immediately transmitted over the DDS to the other CEC units (ships as well as the land-based Fleet Combat Direction Systems Support Activity [FCDSSA] combat system site). The P-3 aircraft provided relay among the

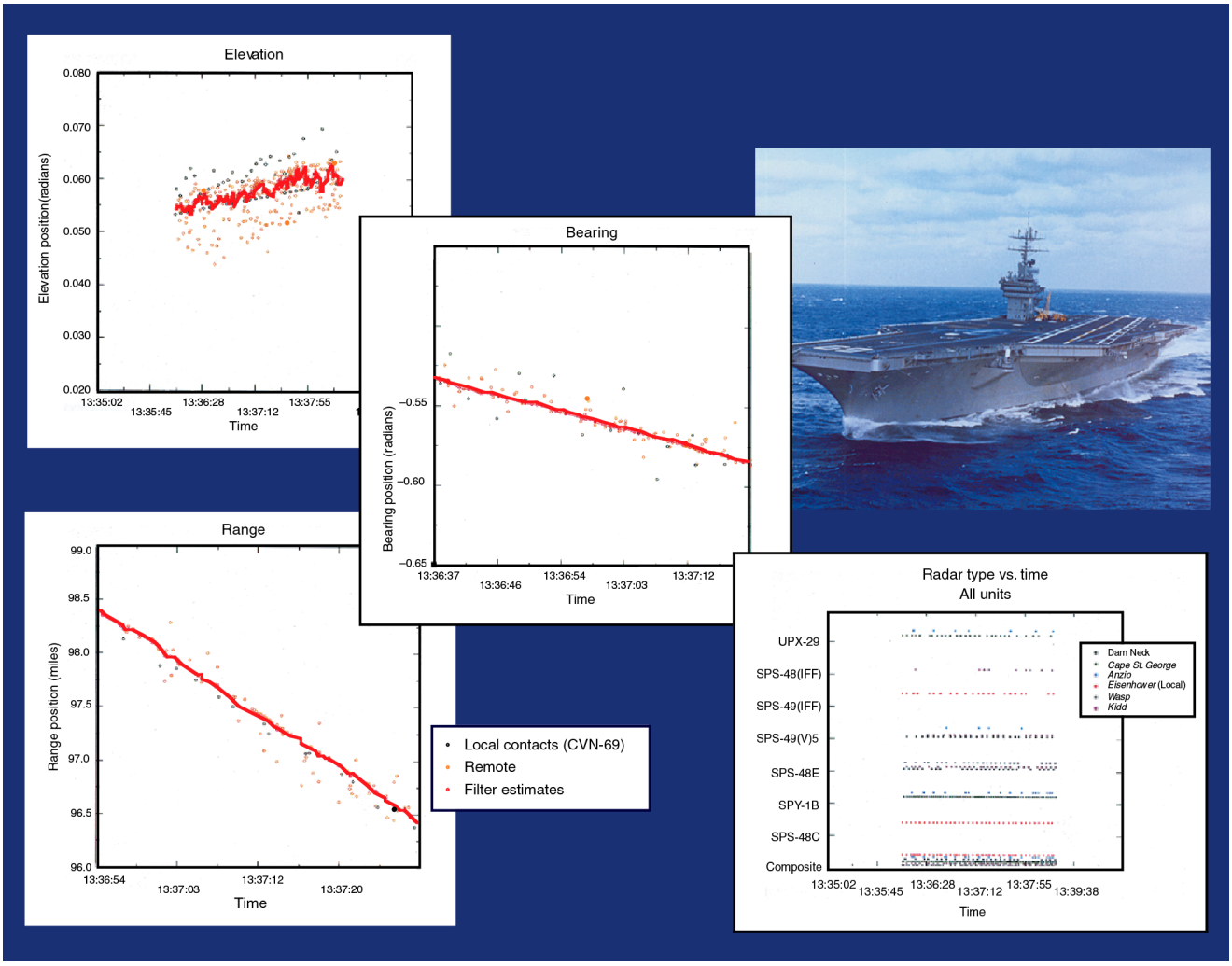

Figure 11. Composite tracking. Shown are local and remote radar and IFF measurements input to a composite track developed by the CEP onboard the USS *Dwight D. Eisenhower*.

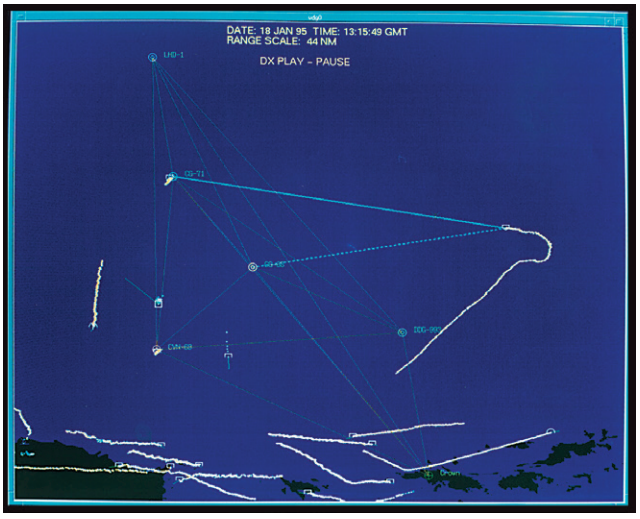

Figure 12. CEC display of the first engagement on remote data. The solid line from CG-71 (USS *Cape St. George*) to the target indicates that an order for engagement has been issued. The dashed line from CG-68 (USS *Anzio*) to the target indicates that the USS *Anzio* is the primary data source for the engagement.

widely separated units as shown. The other Aegis cruiser, USS *Cape St. George*, the NTU destroyer USS *Kidd*, the amphibious ship USS *Wasp*, and the FCDSSA site radar were all cued to acquire the target within seconds. They collectively maintained a single composite track on the target until it splashed. This success has led to new thinking concerning the CEC contribution to theater ballistic missile defense.[2]

In the fall of 1994, the CEC-equipped USS *Dwight D. Eisenhower* battlegroup deployed to the Mediterranean. Although the CEC is yet only certified for test purposes on these ships (a non-CEC mode is required for normal tactical operations), many hours of operation in CEC mode were accumulated during deployment. Figure 15 shows the configuration of a special test event arranged by the Sixth Fleet[3,4] to evaluate the anti-TBM joint capability afforded by CEC. Simulated TBMs generated aboard one CEC-equipped cruiser were networked by CEC and sent via the Tactical Information Broadcast System to interface with a

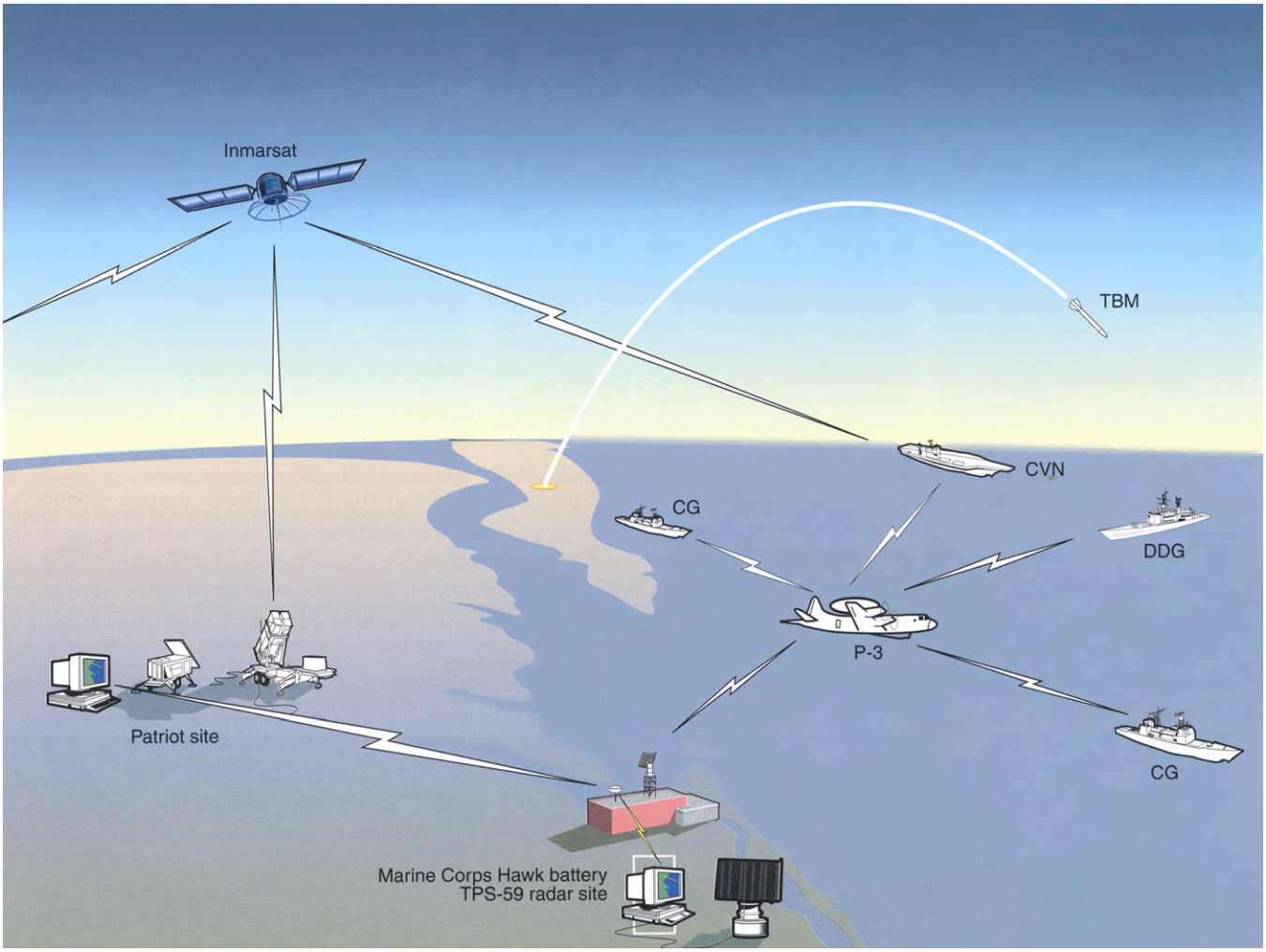

Figure 13. The CEC cueing and composite tracking scenario for JTF-95 battlegroup exercises indicating unit positions and connectivities.

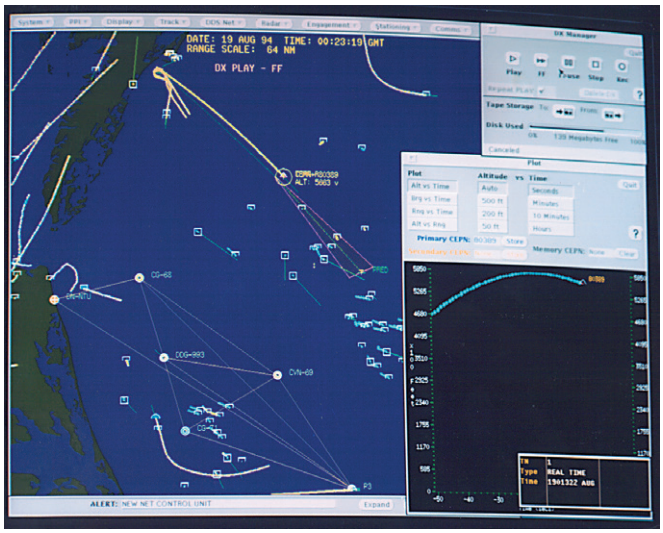

Figure 14. The display indicates the TBM composite track and its track history, its projected impact point and impact uncertainty region, the CEC network, and geographic backdrop. The window in the lower right indicates the TBM's composite track elevation profile.

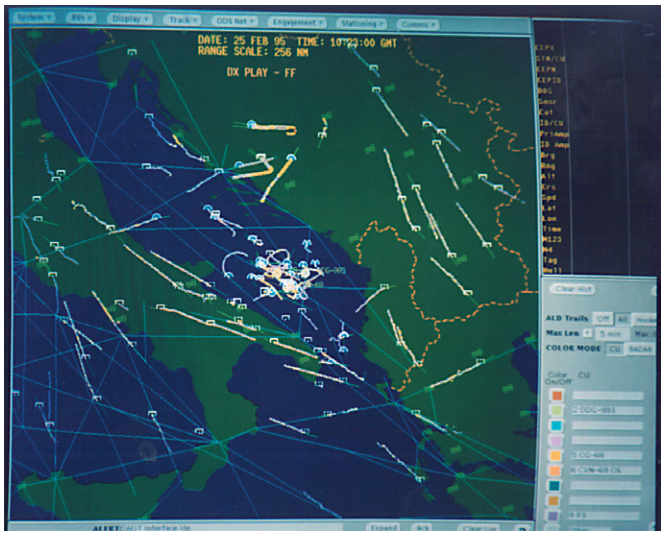

Figure 15. Mediterranean TBM simulated engagement scenario showing the geometries and participants. The simulated TBMs were made to originate from various locations and target Italy.

Patriot radar stationed in Germany. Simultaneously, the CEC composite picture was sent via Inmarsat satellite to the Patriot site from the CVN for display in a workstation. In this manner, the ability of CEC to provide comprehensive data to a Patriot unit was simulated at the command/control level. The U.S. Customs P-3 aircraft was, by now, operating in preliminary tests with CEC interfaced with its radar and IFF systems. Figure 16 is a CEC composite picture obtained when the P-3 aircraft transited to the Mediterranean to participate in the simulated TBM tests with the battlegroup. The airborne CEC unit contributed by extending the composite track and identification picture well inland over rough terrain that blocks shipboard sensors.

The battlegroup returned to the East Coast during 1995 and was scheduled to participate in formal testing of the P-3 airborne CEC unit in preparation for follow-on integration of CEC with the Navy E-2C systems by 1998.[5] The airborne CEC testing will allow instrumented evaluation of its contribution to extend the composite picture for improved Fleet reaction time in the littoral environments. The performance of the DDS network with an airborne terminal will also be formally evaluated. Figure 16 indicates the networking that was evaluated during this test series.

Figure 16. CEC display with part of the battlegroup in the Mediterranean. Shown is the network of the P-3 aircraft, USS *Anzio* (CG-68), USS *Kidd* (DDG-993), and USS *Dwight D. Eisenhower* (CVN-69) with the composite tracks in the Adriatic Sea. (TIBS/ICC I/F = Tactical Information Broadcast System/Integrated Command and Control Interface.)

Additional battlegroup exercises are anticipated for the two Aegis cruisers. Further formal testing of CEC will occur for Fleet introduction qualifications in 1996. At that time, the CEC will be fully certified for tactical deployment.

FUTURE CEC TECHNOLOGY DEVELOPMENT

Common Equipment Set

With Fleet introduction of CEC on an accelerated basis in 1996 and accelerated follow-on production, the Navy is developing a more cost-effective, smaller CEC unit capable of being installed in a much broader spectrum of platforms. The initially deployed units weigh about 9,000 lb. Even the P-3 airborne variant weighs 3,000 lb, which necessitated use of the relatively large P-3 aircraft versus the smaller E-2C for initial testing. Studies show that the tactical version of CEC must be less than 550 lb to allow tactical installation in an E-2C aircraft. In response to this weight reduction requirement, the first CEC Program Manager, Michael J. O'Driscoll, who led the transition of CEC from a technology program to an acquisition program, recognized the need for and directed the development of a new-generation common equipment set (CES). Figure 17 illustrates the reduced-size CES for ship and aircraft integration as compared with the current ship equipment. The CES is planned to be adaptable to mobile land vehicle integration as well. The critical technologies required to produce the CES are readily available:

1. **Monolithic microwave integrated circuit (MMIC) transmit/receive modules** for a cost-effective, efficient, lightweight phased array antenna. This technology itself reduces the system weight by 4,000 lb and substantially reduces required prime power. The prototype array with MMIC modules is currently flying on the P-3 and demonstrating a 35% power-added efficiency per module, which was a world record for efficiency at the time of MMIC pilot production run completion (Fig. 18).

The next-generation module will feature larger-scale integration and manufacturing technology

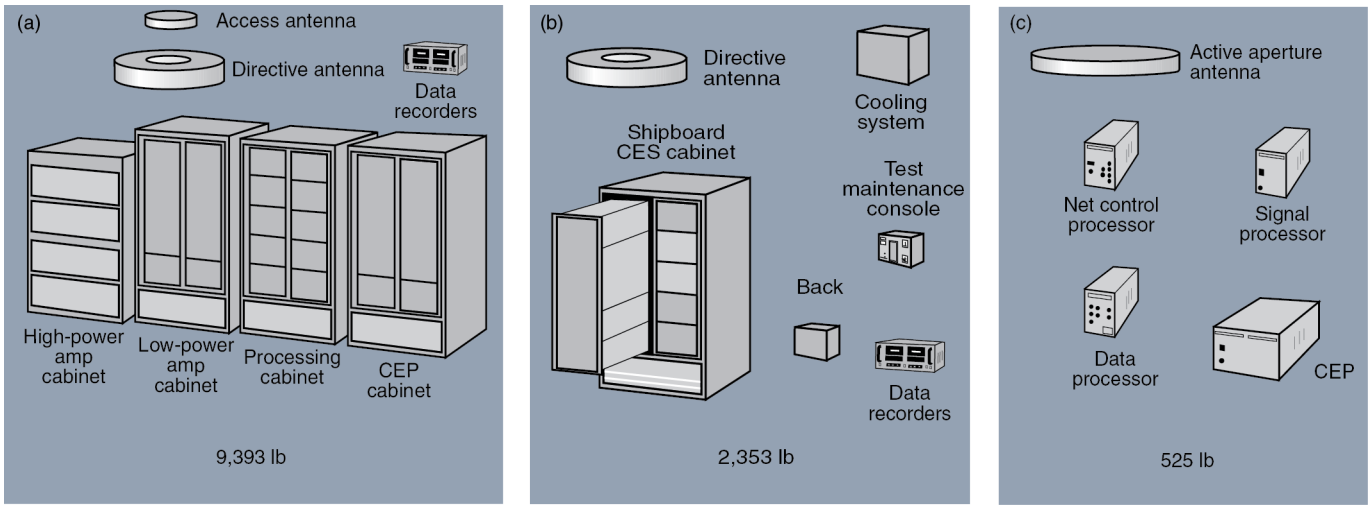

Figure 17. Shown are the major equipment elements of CEC in (a) the present form (IOC system), through (b) Fleet introduction (shipboard CES), and (c) in the primary baseline form as common equipment sets by early 1998 (airborne CES).

Figure 18. Prototype airborne MMIC array. The photograph shows the CEC cylindrical phased array antenna installed on the U.S. Customs P-3 aircraft. The enlarged area shows one of the prototype MMIC modules used in the array.

for lower unit cost, higher yield, and improved life-cycle cost. It is on track for early production with a pilot run completion by 1996. APL sponsored the ITT development of the prototype MMIC transmit/receive modules[5] according to APL-developed requirements and has continued in the lead role with ECI in development of preproduction next-generation modules by ITT and Raytheon.

2. **Application-specific integrated circuit technology** to reduce the number of circuit cards by over 50%, thereby improving reliability and life cycle cost while allowing reduced size and weight. This is an ECI initiative in response to requirements generated by ECI and APL.
3. **New-generation commercial microprocessors based on the Motorola Power PC chip** for increased processing capacity, allowing extension to other joint platforms and advanced cooperative capabilities while reducing size and weight. Use of this processor family will allow flexible in-service upgrades to occur as new-generation processors emerge. Processor architecture and components were selected by APL based on our specifications and knowledge of emerging industry standards.

Several CES engineering development models will be tested with the operational CEC-equipped battlegroup in 1997. Formal fleet introduction will follow operational evaluation that is scheduled for 1998. The CES will be the principal baseline in the Fleet when current-technology units are replaced in 1999. All platform variants will possess common electronics and processors with differences primarily in the cabinets, interfaces, environmental support equipment, and installation fixtures. This CES introduction has been accelerated by direction of the Secretary of Defense as the result of his witness to successful CEC testing in 1994. He was briefed and provided an opportunity to view replays of key AFWTF drone engagements narrated by the APL Test Conductor Arthur F. Jeyes onboard the CVN USS *Dwight D. Eisenhower* at the end of the June 1994 tests. Mr. Jeyes was named Civilian Test Conductor of the Year by the U.S. Department of Defense for his efforts. By the scheduled 1998 operational testing, the CEC CES will have been integrated into Aegis ships, Tartar NTU ships, aircraft carriers, and large amphibious ships of the LHD and LHA classes.

Future Systems for CEC Integration

The CEC will be integrated into the carrier-launched E-2C AEW aircraft by 1998 using the technology base from the P-3 development testing. APL has led the development of the integration approach with Northrup/Grumman Corporation. Following operational testing, it is expected that the E-2C will be operational with CEC by 1999. Not only will the E-2C bring about composite picture extension and network extension (via relaying), it will also allow significantly more complex coordination among manned aircraft intercepts and missile engagements. Currently, substantial effort to maintain keepout zones for flight safety does not provide for optimum manned interceptor and missile intercept coverage in air defense. CEC on both ships and the E-2C, all with detailed, composite knowledge of the air environment, will allow air intercept control and missile engagements within common regions on a per-target basis. Control information to F-18 and F-14 aircraft interceptors based on CEC data will be provided via tactical data links 16 and 4A.

The new-construction U.S. amphibious ship LPD-17 will be integrated with advanced combat system elements under development including CEC and SSDS with APL as Technical Direction Agent for both programs. This will allow the new ship to serve as a nerve center, bridging at-sea and ashore operations and providing a seamless capability for self-defense, cooperative networking, and command/control.

Discussions are under way to develop a common approach for CEC and the Light Airborne Multipurpose Platform III (LAMPS III), an SH-60 helicopter deployed on cruisers and destroyers and currently used primarily for anti-surface and anti-submarine warfare. The approach to be investigated is the use of the CEC in LAMPS to provide for airborne relaying as well as for networking of the LAMPS surface and subsurface functions among ships and LAMPS helicopters. This work involves co-leadership of both the APL Fleet Systems Department and Submarine Technology Department as the technical representatives for CEC and LAMPS, respectively.

Studies have begun concerning integration of CEC into Patriot, E-3 Airborne Warning and Control System (AWACS), and advanced land missile batteries under development, to provide a truly seamless theater air defense and air control across all U.S. military services. Interactions are occurring among the CEC principals (Navy, APL, and ECI) and the government program offices and contractors for each of these programs.

Figure 19 illustrates three phased "snapshots" of a conceptual scenario developed by APL of joint U.S. theater defense against simultaneous attacks of cruise missiles, aircraft, and tactical ballistic missiles. Uprange units first develop tracks for the advancing threats using measurement data networked through CEC, allowing for automatic precision cueing by those units within acquisition range. All units share all sensor measurement updates for independent construction of

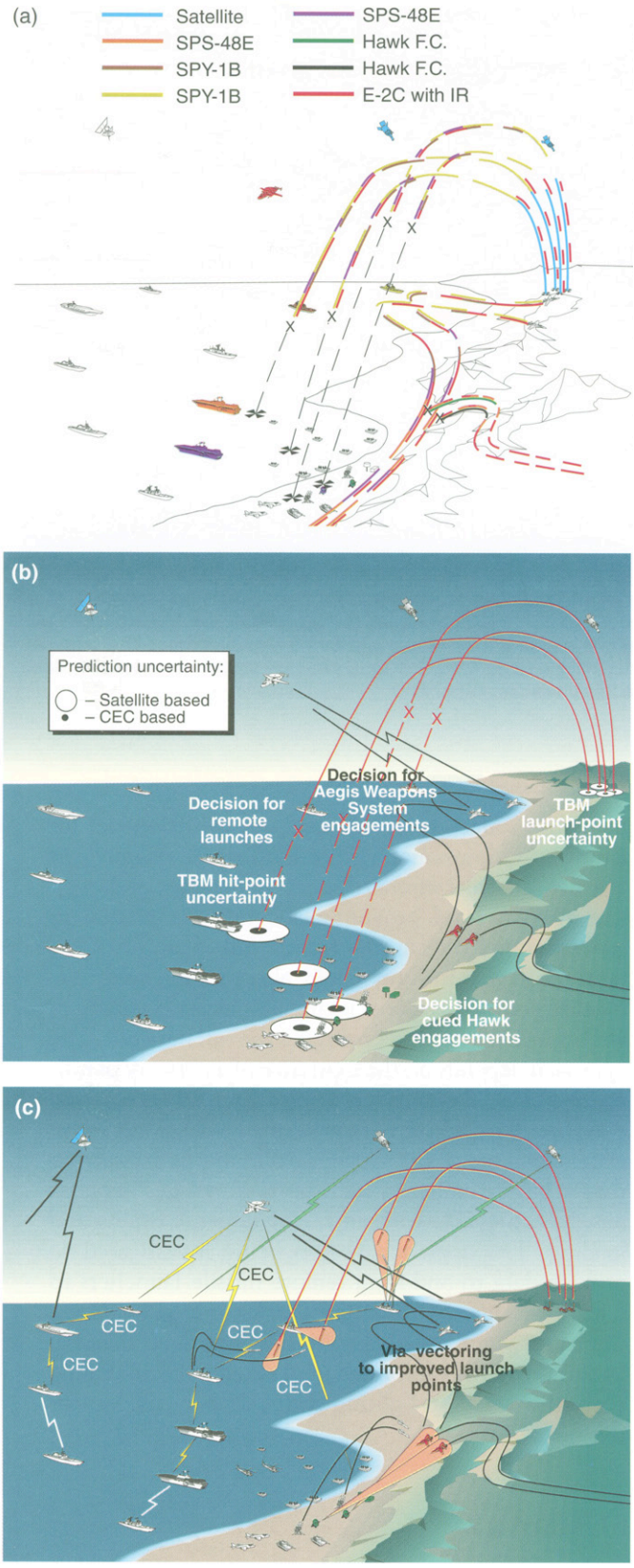

Figure 19. This theater scenario illustrates (a) detection, cueing, composite track/identification; (b) coordinated control of engagements and intercepts against threats and their launchpoints using CEC composite data in conjunction with command/control links; and (c) engagements/intercepts using composite data.

identical composite tracks and identification as well as real-time status of any targets taken under engagement (Fig. 19a). As was determined in the JTF-95 exercise, the composite track is so accurate that a precise launchpoint and impact point can be determined within seconds of composite track establishment for command response (Fig. 19b). As shown in Fig. 19c, strike aircraft can immediately be vectored by E-3 or E-2C aircraft via Link 16, even as incoming aircraft are intercepted by fighters and as incoming cruise missiles and TBMs are scheduled for missile intercept. This situation was tested by the CEC battlegroup in the Mediterranean.[4] Networking of targeting aircraft for launcher image identification cueing and image snapshot transmission over CEC for strike support may be considered later.

Allied Participation in a CEC Network

A strong case can be made for the desirability of participation of Allied nations' systems within a CEC network. Because sensor vantage point is such an important attribute in timely detection and cueing, the more units in a CEC network, the better the coverage. Having the benefit of what every sensor "sees" in an Allied force, as well as the ability of every unit to review the contributions and accuracies of composite tracks in detail, provides system operators and command with an autonomous means to evaluate the situation and reach a more in-depth and timely common understanding of required actions. In an Allied operation the size of Desert Storm, for example, over 50 surface and air sensors could contribute to an identical track and identification picture over thousands of square miles at each unit, allowing a safer coordination of operations and an incisive common focus.

In 1994, a number of Allied countries witnessed the CEC operations of the USS *Eisenhower* battlegroup as guests in VACAPES tests and as participants in exercises in the Mediterranean. Formal discussions are being led by officials of the Navy CEC and International Program Offices. APL is providing the technical support concerning formal agreements to pursue integration and engineering testing with Allied systems and eventual deployment of CEC on next-generation ships or current ships. With the new low-weight, efficient life-cycle CES version of CEC development, testing could begin in several years, and deployment could occur soon after the year 2000.

Advanced CEC Functions

With the quantum increase in information availability through measurement-level data integrated among units in a high-speed net, advanced functions beyond those already described become possible, and several are being developed and pursued by APL.

Cruise Missile Defense

An advanced concept and technology demonstration program related to CEC, called Wide Area Defense, explores advanced sensor cooperation and surface-to-air missile terminal guidance support to greatly extend force battlespace with seamless coverage. A project known as Mountaintop Phase 1 will take place on Kokee Mountain in Hawaii, which serves as a surrogate aircraft platform with a representative sensor and terminal engagement illuminator suite networked via CEC to a CEC-equipped Aegis cruiser.[6] By early 1996, the Navy intends to demonstrate engagement of a sea-skimming drone by Aegis beyond its horizon using the mountaintop sensors and illumination for SM-2 intercept. Figure 20 illustrates the test configuration and the features of a new type of cooperative engagement known as forward pass remote illumination. This project is under the co-technical leadership of APL and MIT/Lincoln Laboratory under Navy CEC Program Management.

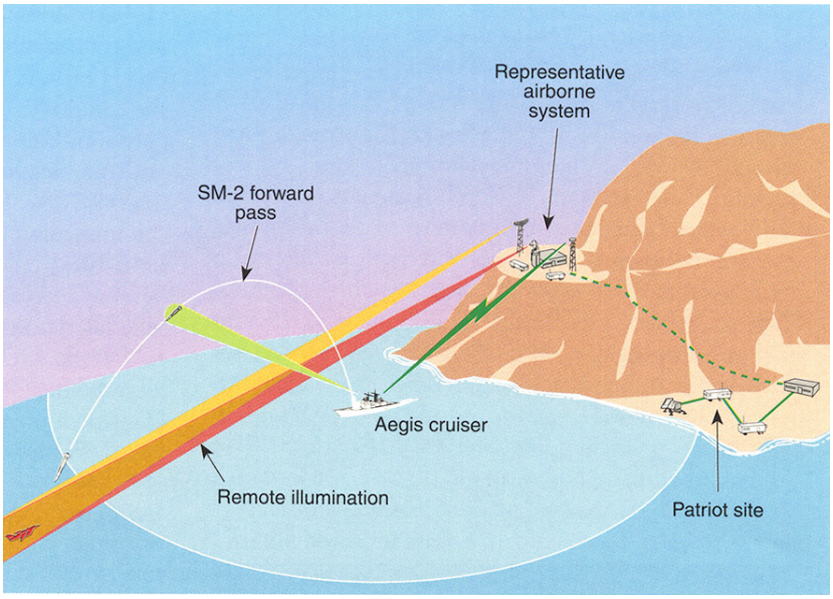

Figure 20. Illustration of Mountaintop over-the-horizon cooperative engagement. The scenario shown will occur in early 1996 near Kauai, Hawaii. The Kokee Mountain site will serve as a surrogate airborne platform for radars and for an illuminator for SM-2 terminal homing beyond the horizon of the Aegis firing unit. CEC provides the fire control quality data transfer to demonstrate this advanced capability.

In a related effort, the Army and Navy have agreed to initial mutual data collections during the Hawaii Mountaintop testing to obtain data relevant to potential Army use of an airborne fire control sensor for over-the horizon engagements and relevant to the potential contributions of CEC Link 16 to joint air defense (Fig. 20).

Tactical Ballistic Missile Defense

Early testing and analysis of CEC against TBMs indicate the potential for a significant contribution in terms of allowing the collection of sensors to maintain a single composite track of sufficient quality for missile intercept, with real-time status of engagements and real-time recommendations of the unit(s) with the highest probability of successful engagement. With future precision sensors capable of supporting precision composite tracking of a TBM, it may be possible to resolve the reentry vehicle from a complex of reentry decoys and debris and even to determine the wobble motion of the target via a new cooperative resolution approach. In this concept, resolution and tracking of the object field could guide a kinetic-kill interceptor to the correct target. A CEC engineering test last year of target-resolving techniques provided early encouragement for this approach. The concept is illustrated in Fig. 21.

Miniaturized CEC Unit

In the longer term, we envision the potential for a low-cost, low-weight, mini-CEC unit available at the fighter/strike aircraft, attack helicopter, and even the platoon level providing a composite picture as processed and transmitted from a full-capability CEC unit. Such a mini-unit could also provide selective, local region composite tracking and weapon cueing as well as measurement reporting to the full network. The approach depends on the existence of a network of full-capability CEC units developing a complete composite database. Early design assessment of such a mini-unit using elements of the CES by APL and ECI indicates that a large number of such units in a CEC network may be achievable without taxing network timing and loading. The approach is also being investigated to provide data to and from remote missile launchers to a full-performance CEC unit for distributed land missile battery and joint Navy/Marine ashore air defense. In this way, a truly informed joint allied force, including even the smallest fighting units, is conceivable for the future.

SUMMARY

The CEC was developed in response to the need to maintain and extend Fleet air defense against advanced, next-generation threats as well as to complement advances in sensor and weapon systems. By

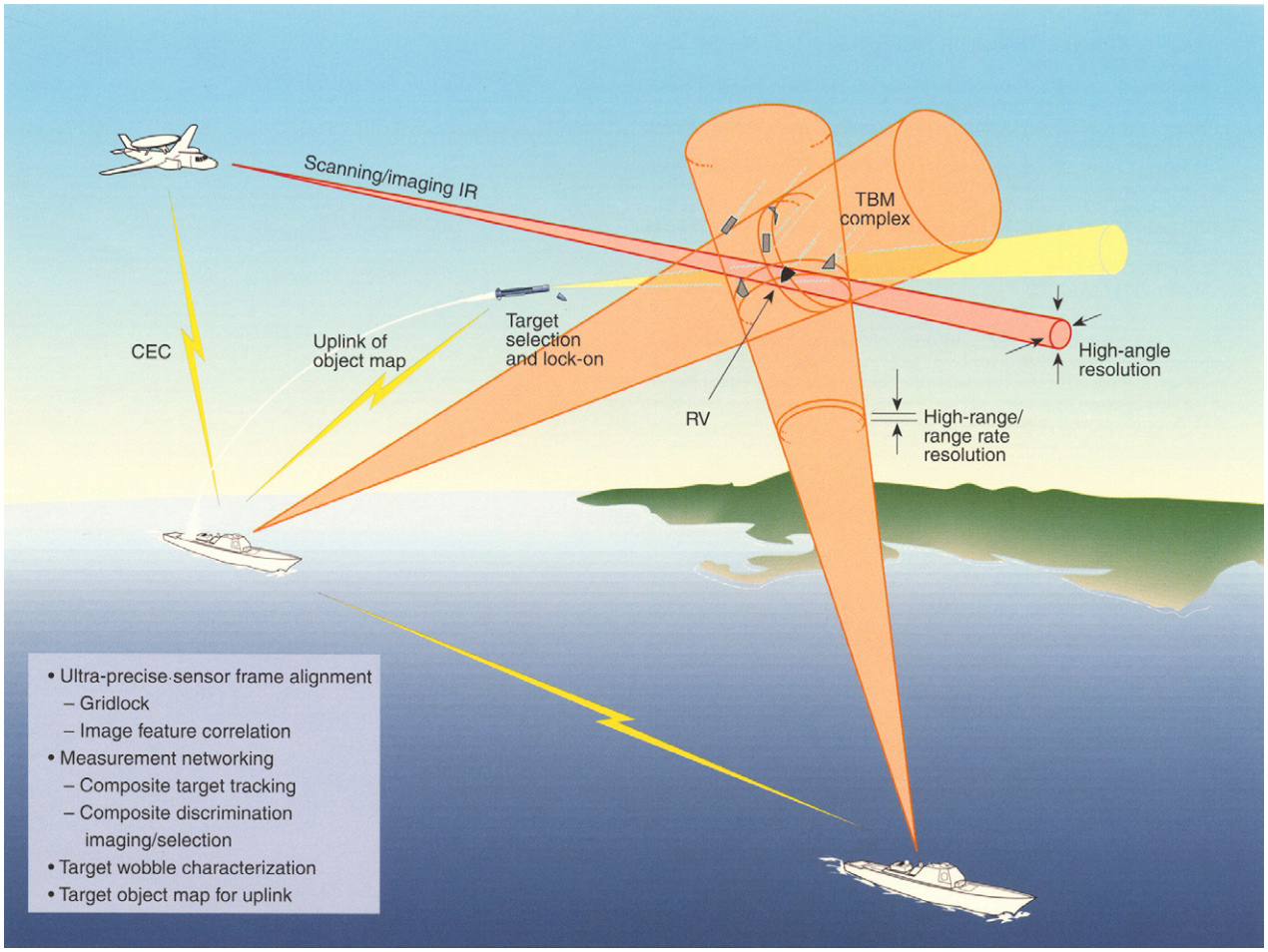

Figure 21. Tactical ballistic missile cooperative resolution. CEC offers the potential to process data from multiple sensors with very high resolution in one dimension to create a precision map in three dimensions to support kinetic-kill interceptor guidance to the reentry vehicle amidst decoys and debris. The precision and rapid update rate of the mapped objects could also allow the interceptor to account for target wobble or tumble.

networking at the measurement level, each unit can view the theater air situation through the collective sensors of the combatants, and units are no longer limited in knowledge of air targets and in missile intercept range by the performance limits of their own sensors. The result is a quantum improvement in which advanced threats may be composite-tracked and engaged using remote data by networked units that would otherwise not have been able to track or engage them. In a 1994 *U.S. News & World Report* article,[1] Rear Admiral Philip Coady, Jr., Director of Navy Surface Warfare, observed about CEC that "the composite picture is more than the sum of the parts."

In providing the improvement in air defense performance, CEC has been recognized by Congress, DoD, and the Navy as dissipating the "fog of battle" by virtue of composite tracking and identification with high accuracy and fidelity resulting in an identical database at each networked unit. A new generation of precision coordination and tactics has thus been made possible, as recognized by the USS *Eisenhower* battlegroup command and staff. Further, substantial theater-wide air defense and coordination enhancements are possible in the joint arena by CEC integration into U.S. and Allied Air Force, Army, and Marine Corps sensors and air defense systems. This potential has led to congressional and DoD direction that the services explore joint CEC introduction.

The CEC is the only system of its kind and is widely considered as the start of a new era in war fighting in which precise knowledge is available to theater forces, enabling highly cooperative operations against technologically advanced and diverse threats. APL has played the lead role as inventor, technical director, and partner with industry and government to introduce this cornerstone capability.

REFERENCES

[1] Aster, B. B., "When Knowledge is Military Power," *U.S. News & World Report*, 37 (24 Oct 1994).

[2] Morrocco, J. D., "US Navy Battle Group to Test New Missile Defense Concept," *Aviat. Week Space Technol.*, 28–29 (30 Jan 1995).

[3] Bickers, C., "CEC `Scud' Defense Shown in Europe," *Jane's Defence Weekly*, 3 (11 Mar 1995).

[4] Dornheim, M. A., "Navy Starts Flight Test of Radar Data Network," *Aviat. Week Space Technol.*, 40–41 (18 Apr 1994).

[5] Frank, J. and O'Haver, K. W., "Phased Array Antenna Development at The Applied Physics Laboratory," *Johns Hopkins APL Tech. Dig.*, **14**(4) 339–347 (1993).

[6] Starr, B., "USN Looks Over Horizon from Mountain Top," *Jane's Defence Weekly*, 8 (29 Jan 1994).

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