



E-2C Hawkeye Combat System Display

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The E-2C Hawkeye aircraft has been an important asset to the Navy for over three decades, providing airborne early warning command and control support to carrier battle groups. The Hawkeye 2000 program is a major enhancement to the E-2C's capabilities. The Advanced Control Indicator Set (ACIS) hardware, using software developed by APL, provides the critical user interface to the aircraft's sensors and subsystems. Improvements to ACIS incorporate commercial off-the-shelf hardware and software components and a modern graphical user interface, thereby increasing the performance and flexibility of the display at considerable cost savings. The result is a combat system that makes a significant contribution to the overall situational awareness and tactical effectiveness of the E-2C and the modern battle group.

INTRODUCTION

Over the past three decades, the E-2C Hawkeye aircraft has provided valuable airborne early warning command and control (C2) support to Navy carrier battle groups. A significant capability upgrade known as Hawkeye 2000 (H2K) has been undertaken to ensure the E-2C's continued effectiveness in the advanced threat environment and joint operations architecture of the 21st century. H2K introduces a number of advanced systems: an upgraded mission computer (MC), a new electronic support measures (ESM) passive sensor system, the Cooperative Engagement Capability (CEC) sensor network system, and Advanced Control Indicator Set (ACIS) displays. ACIS provides the crucial human-machine interface (HMI) between E-2C operators and these new systems by combining control and display of radar and identification friend or foe (IFF) sensors, CEC, MC, ESM, and tactical data link information.

In the mid-1990s, APL was selected by the Naval Air Systems Command to lead the software development of the new ACIS displays, as well as to facilitate the integration of CEC. The new displays take advantage of the latest commercial off-the-shelf (COTS) hardware and software, use network technologies and a modern graphical user interface (GUI), and add greatly to the overall situational awareness and tactical effectiveness of the E-2C and today's modern battle group.

BACKGROUND

E-2C Mission and Capability Evolution

The E-2C is a carrier-based airborne early warning C2 aircraft used by the Navy¹ (Fig. 1). Distinguishable by an elevated radar dome on the top of the fuselage, the twin turboprop aircraft provides combat air defense



Figure 1. E-2C carrier takeoff. The E-2C is a carrier-based airborne surveillance aircraft which has served the Navy and the United States since the 1970s.¹

support for the carrier battle group. The early warning radar, along with other sensors, allows the E-2C to see airborne targets at great distances and, therefore, gives a long-range target detection capability to the battle group. The fuselage consists of a front cockpit with flight controls for the pilot and co-pilot, a forward compartment for combat systems equipment, and a rear C2 center with a control indicator set (CIS) at each of three mission system operator positions. Each identical display terminal provides full interface to aircraft systems through the MC. Operators include the Air Control Officer, the Combat Information Center Officer, and the Radar Officer (Fig. 2). Each officer executes specified independent tasks in support of the aircraft mission, essentially to detect and track targets, communicate pertinent information to other participating units, and direct aircraft operations in support of the battle group.

The E-2C program, initiated in the late 1960s as an upgrade to the Navy's E-2B Fleet, led to a successful prototype flight demonstration in 1971, followed by Fleet introduction in 1973. During its service, the E-2C has undergone a number of modernization programs to increase its capabilities as requirements changed and



Figure 2. E-2C ACIS operators (photo courtesy of Northrop Grumman).

technologies improved. The first major upgrade to the E-2C, designated Group 0, replaced the AN/APS-125 with the AN/APS-138 as the primary radar sensor. Later, Group I configuration modifications provided improvements to the engines and cockpit instrumentation as well as upgrades to several antennas. More significantly, Group I also introduced the updated AN/APS-139 radar, which increased target tracking capability and resistance to electronic countermeasures.

In the early 1990s, the Group 0 and Group I aircraft began a transition to a new Group II configuration. A new radar, the AN/APS-145, increased target detection range and further improved tracking capabilities. The MC, the main combat system in the aircraft, was upgraded to increase speed and functionality, and operator displays were improved. The Joint Tactical Information Distribution System (JTIDS) data link provided an enhanced capability to communicate with other members of the battle group and joint forces, and the Global Positioning System (GPS) improved aircraft navigational accuracy.

The E-2C's first combat deployment was in Vietnam, and it has played pivotal roles in strikes against Libya, Operation Desert Storm, and the campaign in Kosovo.

The first ACIS/MC upgraded E-2Cs were provided to operational Navy squadrons in April 1999. The VAW-117 squadron used these aircraft for Caribbean drug interdiction work in September 1999. Officers of the squadron stated that the ACIS/MC system on these missions "proved itself to be a giant leap forward for the Airborne Early Warning, and Command and Control Community."² In October 2001, Northrop Grumman delivered the first of 21 H2Ks to the Navy.

The ACIS/MC upgrade is being used in the war in Afghanistan, where E-2C aircraft from USS *Carl Vinson* (CVN 70) are aiding in wartime missions. These aircraft carry the ACIS and MC upgraded systems but are not equipped with the pending CEC or ESM upgrades.³

Hawkeye 2000 Upgrade

The H2K upgrade to the E-2C, managed by the Naval Air Systems Command's PMA-231 E-2C Program Office and led by Northrop Grumman as the systems integrator, represents a major aircraft modernization effort in support of the Navy's evolution toward network-centric warfare operations. In addition to numerous mechanical improvements, H2K includes integration of the CEC, a new ESM passive sensor system, a new MC, and new ACIS operator displays.

CEC is a Navy-developed sensor network system designed to enable diverse air defense systems to operate as a single distributed theater air defense system. The system derives sensor information from CEC-equipped cooperating units (CUs) and provides a single integrated air picture (SIAP) of composite tracks through near-real-time exchange of sensor measurement data

among CUs. The CEC network design exploits the advantages of the geographic and technical diversities provided by each CU and sensor to yield a low-latency SIAP with accuracy and consistency superior to that of any single CU or sensor (Fig. 3).

As an integral part of CEC-equipped battle groups, the H2K E-2C will make important contributions to the CEC SIAP such as long-range track initiation of low-altitude and terrain-masked targets, cueing to fire control sensors (e.g., Aegis), and connectivity among beyond-the-horizon CEC CUs. The composite tracking improvements provided by the CEC sensor network to E-2C will enhance composite track accuracy and update rates, increase aircrew situational awareness, and improve overall mission effectiveness.⁴

Another important attribute of the SIAP is target identification (ID). The newer ALQ-217 ESM system will provide target detection and ID performance superior to the older ALR-73 Passive Detection System (PDS).

The addition of new CEC and ESM systems to the existing sensor systems suite (AN/APS-145 radar and APX-100 IFF), GPS, and data links (Link-4A, Link-11, and JTIDS Link-16) necessitated significant changes, including size and weight reduction to the MC. The new MC, based on Raytheon's Model 940 DEC alpha computer,⁵ incorporates a UNIX operating system, four processors, increased speed and memory, and better maintainability than the larger and heavier legacy L-304 MC. The myriad E-2C system data are processed and correlated by the new MC, then provided to ACIS for operator interface, display, and system control.

The Navy selected APL to lead the ACIS software development effort. As the design agent for CEC, the Laboratory had been instrumental in CEC development and integration on the E-2C, as well as development of CEC displays for surface combatants.⁶

The Naval Air Warfare Center Aircraft Division (NAWCAD), designated by the Navy to become the eventual system support activity for ACIS, also provided key participation on the software development team.

THE ADVANCED CONTROL INDICATOR SET

Navy Requirements

Many ACIS requirements grew out of a larger Navy modernization effort aimed at replacing obsolete Navy computer equipment and systems with modern ones that could keep pace with rapidly evolving technology. The most basic requirements included maintainable in-service hardware and operating systems capable of accommodating certified legacy software without major modifications. There was an emphasis on using COTS products for cost savings, where possible, without jeopardizing the maintainability, supportability, and future software upgrades of systems, especially display systems.

As an objective, the Navy also desired a common HMI among display systems for C2 platforms, including surface combatants (especially Aegis cruisers and aircraft carriers) and the airborne E-2C. With a common HMI, Navy personnel can more easily move among and operate on different platforms with minimum retraining. A common display HMI also offers the advantage of better communication and coordination among various surface and air C2 operators. Commonality objectives included a standard windows-based color display workstation with a portable operating system and point-and-click control devices, as well as a keyboard. While there was general agreement across Navy platforms on the fundamental ingredients for a C2 windows-based display (e.g., geographic plots of object positions and information readout panels for selected objects of interest), fully generic display elements would not provide optimal support for unique platforms with unique missions.

For the E-2C ACIS, a tailored design was required to satisfy airborne-specific mission tasks that differed greatly from those of surface ships. Factors included the multiple interfaces with numerous aircraft systems, limited manning, operator versatility, and operator preferences. Because of multiple system interfaces, E-2C mission systems operators have a very heavy task load. CEC, data links, ESM, and more capable radar and IFF sensors add significant track loads to an already demanding mission environment. The three operators (compared to

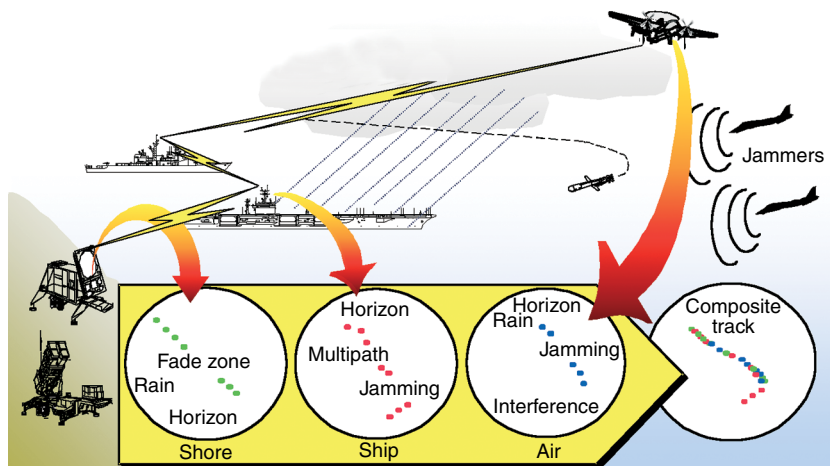


Figure 3. CEC sensor networking. The composite tracking concept provides a coherent, highly accurate track picture held by all units in a common, shared database. CEC nets sensors, exchanges sensor measurements among all netted sensors, and fuses data to create a composite track.

more than a dozen on a surface combat system) share the duties of systems operation, air control, and coordination with the battle group. However, most E-2C operators are capable of and are often required to perform any function based on mission demands. Therefore, each ACIS station must be able to accommodate all tasks simultaneously with the other two stations.

Hardware

The ACIS display hardware selected for the E-2C is a customized version of the Navy AN/UYQ-70 (Q-70) hardware standard. For the airborne ACIS, it was necessary to reduce the weight of the equivalent shipboard Q-70. Lockheed Martin designed a special low-weight VME computer chassis for the ACIS to satisfy this requirement, achieving a final ACIS weight of 63 kg.

Operator input devices are contained in the bullnose, a retractable operator control unit containing a keyboard, trackball, primary hook button, keypad, and force stick (Fig. 4). It is retractable by necessity to allow the operators access to the cramped operations compartment of the E-2C. The bullnose data input devices are designed so that each has a redundant backup, with the single exception of the keyboard. If required, the force stick can handle the track ball input; the primary hook feature can be performed through the hardware variable action button (VAB) keypad.

An important feature of the upgraded H2K ACIS is that the main computer is implemented with COTS hardware. The COTS components comply with various industry-recognized standards of construction, behavior, and design. Thus, they can be used for a wider set of tasks, resulting in lower cost as well as easier maintenance and technology upgrades. This satisfies a general

desire in the military to reduce cost and at the same time more effectively respond to ever-faster advances in hardware capability.

Another advantage is that the ACIS software can run on any compatible UNIX operating system on a variety of COTS hardware. This makes training easier outside of the aircraft because the specific aircraft hardware is not required. With the exception of the VAB keyboard and the radar video (unique hardware modules installed in the Q-70), commercial laptop computers can be used for ACIS training.

ACIS applications are stored and loaded to the display hardware from a disk called a removable media cartridge (RMC). The RMC is based on a COTS industry standard known as the Small Computer System Interface (SCSI). The Navy must have a dependable source of replacement hardware well into the future for the H2K project. Historically, this requirement was accommodated by a large initial purchase of spare hardware to provide for the life of the program. Because the SCSI is an upgradable standard, parts can be purchased on an as-needed basis. This removes the risk of initially purchasing too many parts or using up parts that are no longer produced by the original vendor. Already, the ACIS project has successfully weathered the obsolescence of SCSI drives because of size, from 1 Gbyte originally to 9 Gbytes (currently) to 18 Gbytes in the near future.

Because the RMC is a removable cartridge, classified data are removed with the disk at the end of the mission. This allows the classification level of the aircraft to be reduced when it is unoccupied, easing many issues of security, lockdown, and guarding of the E-2C.

One unique hardware feature of ACIS is a combination radar interface board (RIB) and radar scan converter (RSC) board developed by DRS Technologies. This enables simultaneous display of the real-time radar video displayed on top of the geographic maps and underneath the corresponding computer-generated track symbols. These boards use the COTS software standard X Windows and C++ interface libraries, which simplify software development.

The original CPU used by the ACIS was the HP743 embedded processor. During ACIS development, the HP743 became commercially obsolete, and the faster HP744 has replaced it in all current ACIS displays. Continuing improvement of CPU technology is now leading to the obsolescence of the HP744 and migration to the UltraSPARC CPU as the Q-70 platform. The ACIS will also migrate to the Ultra-SPARC Q-70.

Architecture

System

The E-2C combat system consists of three identical ACIS workstations and one MC. The CEC system



Figure 4. The ACIS airborne Q-70 display console referred to as "bullnose" after its characteristic shape.

consists of two primary components: the Cooperative Engagement Processor (CEP) and the Data Distribution System (DDS). The CEP handles track information processing, while the DDS is responsible for the distribution of track data across the CEC network. The system architecture integrating these components was designed jointly by APL, Northrop Grumman, and NAWCAD.

The ACIS workstation is the primary HMI for the E-2C systems. The workstations communicate with the MC, CEP, and DDS through a 10-Mbit/s display local area network (LAN). Additionally, each workstation receives video information directly from the radar and IFF subsystems. The MC and CEP share sensor data on a separate, much faster 100-Mbit/s Ethernet network called the CEC LAN.

Control of all sensors, data links, and CEC is performed through the ACIS. An overview of the system's architecture is presented in Fig. 5. The design of this system allows the E-2C operators to perform their duties even if several system components have failed. Additionally, the MC will still function and provide data to the ACIS even if some (but not all) of its sensors and data links are unavailable. Because the ACIS workstations are identical, failure of any of them will still allow the E-2C to perform its mission.

Aircraft equipped with CEC have four possible modes of operation depending on whether the MC, CEP, or DDS is inoperative: tactical, MC failure, stand-alone, or relay mode. Tactical mode indicates full tactical capability, i.e., all three of these subsystems are operational. In this mode, the ACIS workstations receive track data primarily from the MC. However, the CEP and MC exchange their track data continuously. The MC will attempt to correlate tracks reported by its local sensors to tracks reported by the CEP from other units in the CEC net. When two tracks are correlated, the CEP track is automatically inhibited from display on the ACIS. Conversely, the CEP will attempt to correlate data from the MC and share this information with other units in the network.

MC failure mode can be selected when the MC is disabled and allows the ACIS to accept tracks directly from the CEP. In this mode, the aircraft sensor information is not displayed and contributions are not made to the CEC network. However, information coming from CEC will be displayed. CEP- and DDS-related functions can still be performed in this mode of operation.

In stand-alone mode, the DDS is off-line and the MC and CEP are operational. In this case, data from

local sensors will be displayed on the ACIS, but no communication is possible with the CEC net. Track data will continue to be exchanged between the MC and CEP, but CEC functionality will be limited.

In relay mode, the CEP is off-line and the MC and DDS are still operating normally. The ACIS will display data from local sensors, but no contributions will be coming from or going to the CEC net. However, the aircraft can still function as an airborne relay in the network, allowing additional lines of communication between cooperating units. This can be very beneficial if two surface vessels equipped with CEC are too far apart to communicate directly with one another.

Communications

A significant enhancement of the ACIS is the incorporation of industry-standard network communications tailored to fit the need for reliability in the communications process. APL chose to develop a tailored communications interface to ensure reliability while maintaining speed. This resulted in the creation of a high-speed, high-fidelity communications interface.

The ACIS uses a combination of the TCP and UDP industry-standard protocols for communicating information with other systems on a computer network. In previous combat systems, specific and often unique communications protocols were developed to link individual systems. The use of standard protocols gives the ACIS the advantage of a consistent interface to communicate with external systems. The employment of a common standard such as TCP allows for future growth, supports multiple platforms, and allows for more flexibility.

The ACIS uses TCP and UDP in clearly defined roles. TCP, a point-to-point protocol, provides reliability of communications but at the expense of speed. It is employed when large amounts of data

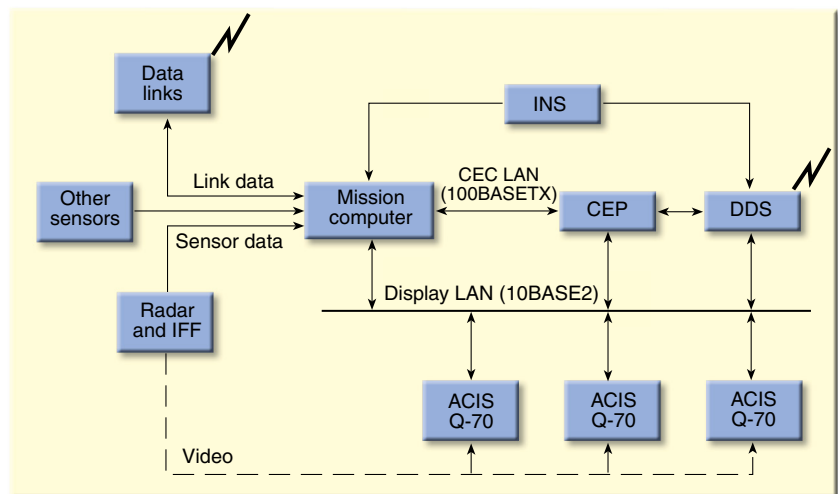


Figure 5. The ACIS architecture overview showing data connections (solid lines) and the radar video distribution (dashed line).

need to be transferred reliably (e.g., at system initialization) and to ensure connectivity between the ACIS workstations and the combat systems. UDP is connectionless, meaning that a server system broadcasts data to a particular port, and any interested clients receive and process the information. Unlike the TCP interface, UDP does not have guaranteed delivery, but it is much faster than the TCP and uses less network bandwidth when sending the same information to multiple recipient workstations.

Because of the speed at which UDP data are transferred, the MC uses UDP to communicate track and tactical information to all three of the ACIS workstations aboard the E-2C. However, since reliability and consistency are important in the data presented on the ACIS, an additional layer of processing to the UDP was invented and developed by APL and Northrop Grumman. This additional layer ensures reliability in the UDP data that have been transferred from the MC, while still maintaining the speed and low-bandwidth benefits inherent in using UDP. The ACIS does this by keeping track of incremental sequence numbers embedded in the UDP data. If a missed message is detected, an ACIS workstation will request a retransmission of the data from the MC.

Wrapped in many of the TCP and UDP messages that are sent to and from the ACIS are interface messages, which are the primary means of communicating information between the ACIS and the MC. The MC supports a large number of interface messages, so to accommodate them, an object-oriented programming approach was taken. This had four advantages: (1) the object-oriented design helps organize the messages into a comprehensible structure, (2) the design helps system performance by providing rapid array lookup tables for quick MC message and acknowledgment processing, (3) new message functionality is easily introduced (e.g., the addition of new ACIS windows and functionality can be quickly and easily interfaced into the message processing library), and (4) because of the object-oriented layout of the messages, other projects can easily use the message processing library functionality that is provided.

Besides using the TCP and UDP interface to transfer information, the ACIS also can share files (e.g., various configuration, overlay, and log files) and communicate information among workstations. To allow the operators to share the files, a standard UNIX file-sharing process was used. The MC RMC is employed as the single point for data storage. This allows all three ACIS stations and the MC to share data from one single area. In case of any type of file-sharing failure, the operator is notified with an alert on the Plan Position Indicator (PPI). When information must be communicated among ACIS stations, a UDP protocol library that is built into the software is used. The ability of the workstations to share files

and communicate adds to the capability and flexibility of the ACIS communications interface.

Software Design

Graphical User Interface

Probably the most fundamental improvement of the ACIS H2K system over the previous E-2C design is its use of a modern PC-like raster display GUI. The original CIS used a vector graphic display that could draw objects only out of a combination of line segments and curves. Vector displays also do not show filled objects but merely simple outlines. In contrast, a modern raster display can draw objects that are pixel filled or outlined. Further, a modern GUI breaks up the displayed area into multiple windows. This is useful because multiple applications are then displayed within movable and rescalable windows on one display screen. The operator can then position the applications to best support the current task. GUIs also convey information more efficiently than older text or vector displays because of their use of rich images and graphics. Visual data are more quickly processed by the operator than text data.

In the CIS, some of the system functionality was implemented as hardware controlled by switches and knobs on either side of each display. Simultaneous control of this hardware by three operators required either replicating the same hardware at each station or limiting the control of that function to a particular operator. CIS control duplication added weight to the aircraft and reduced new functionality that could have been implemented in that place. In addition, limiting control to a particular officer increased operator stress if that operator was already busy but had to commit an action immediately.

In the ACIS, much of this hardware is controlled via software, so all functionality is available at any station. The GUI software design implementation results in a large increase in system ability and ease of use compared to the CIS system. A nearly unlimited number of capabilities can be handled by such a GUI that is only limited by the power of the hardware and the ability of the operator to manage interface complexity. In the ACIS, the complexity issue is mitigated by minimizing the number of unused panels to a compact list of buttons on the ACIS taskbar panel and launching panels from hierarchical pull-down menus. Control panels are also logically arranged in the HMI specification to improve their usability and manage interface complexity.

COTS Software

The ACIS is implemented in software written in standardized COTS languages and software libraries (C/C++/X Windows/Motif) on UNIX operating systems (HP-UX, Sun Solaris, and Linux) and compiled

via the open-source GNU GCC compiler. Open-source software is freely licensed, can be examined, and is not controlled by a central authority. HP-UX is the operating system for the ACIS on the aircraft, but this use of flexible UNIX platforms also allows the ACIS to be operated on the open-source Linux and the commercial Sun Solaris operating systems. Open-source software has a further advantage beyond COTS software in that it is not linked to any particular corporation. A corporation may go bankrupt or decide to cease production of a particular product, resulting in a loss of support; open-source products do not have this problem.

The COTS software tools used to develop the ACIS were also based on open software, including the GNU *gdb* software debugging tool and the GNU *gprof* performance profiling tool. X Windows and Motif are freely available software products and were employed in the project to implement the displays. The use of these products greatly reduced cost and licensing difficulties during software development.

Throughout the H2K program, the ACIS will continue to be modified and improved. It will be easy to find software engineers who can do these upgrades because of the application of the industry standard C/C++ language and open software tools.

The ACIS uses TCP/IP to pass messages among the ACIS workstations and the MC. This improves software stability and reduces code complexity by using the solid and tested TCP/IP software support already present in the UNIX operating system.

Common Display Kernel

The Common Display Kernel (CDK) is a repository for reusable display software that helps to provide a common user interface within the battle group while allowing seamless integration of multiple project components into one combat display system.⁶ Specifically, CDK brings the idea of a windows-based display system to the operator and is the basis for a number of other combat system displays, including the Aegis and Ship Self-Defense System. Providing a common user interface is significant because it makes training concepts more familiar. Other members of the battle group will also be able to communicate information more effectively because they will be using similar windows and functions offered by CDK.

CDK provides a robust yet generic capability to display information using a common toolset. Included in the CDK package are tools that can easily be used to extend its capability, which makes it adaptable for the integration of multiple project requirements. CDK is the basis for the CEC display system; it was chosen for the E-2C based on its generic nature and the need to incorporate CEC functionality into the ACIS display. CDK is layered so that it is easily adaptable to growth by a number of projects.

To support the ACIS, CDK has been extended in a number of significant ways for the E-2C mission. ACIS has also enhanced and optimized the display functionality provided by CDK to create a more efficient and streamlined display product. As more projects use CDK, its overall capability and functionality are improved.

Application Level

The application-level design consists of many individual panels, each having the ability to be independently designed and developed. This allows for a more robust operation and makes the system easier to maintain and troubleshoot.

As noted previously, the software design made extensive use of preexisting CDK libraries which provided a quick generation of working GUI panels for the operator. The control panels convey information via a readout or graphical update on the PPI. The operator may then view or alter the information, which in turn updates the ACIS, MC, CEP, or DDS systems.

CDK libraries also were the basis for specific databases. For instance, the CDK generic track file database provides a common data area for storing MC and CEC information. E-2C ACIS-specific information was added to the CDK generic track file. By using this generic track file, other CDK written processes can manipulate E-2C's main tracking information.

CDK also provides data generators that process data into a PPI readable state. The PPI reads the preprocessed data and rapidly draws the information. Since the E-2C ACIS was built on the preexisting CDK track file and data generators, displayable E-2C symbols and tracking information on the PPI were available in a relatively short period of time.

To form the network interface between ACIS and other systems (e.g., MC, CEP, DDS), the CDK common network interface library was used. This library includes mechanisms for rapidly queuing, retrieving, and handling a large number of network buffers. CEC message processing was taken directly from the shipboard CEC display system, and E-2C-specific message processing was added to form the complete network interface for ACIS.

In addition, the software was designed to support preflight mission planning in conjunction with a separate Navy planning system in the squadron ready room. Required mission planning capabilities included updating geographic data, preloading mission parameters (special points, flight plans, and graphics overlays), and presetting operator configuration preferences.

Human-Machine Interface Features

Overview

There are several essential HMI ingredients for any Navy C2 windows-based display. First, it must have a

tactical situation (TACSIT) PPI window with geographic displays and overlaid symbols. Second, there must be a character readout (CRO) display window with information about selected objects in the TACSIT PPI window. After providing these two necessary windows, the display can then be enhanced with other windows and controls that customize it to satisfy platform-specific mission requirements.

Because the PPI window is the focus of an ACIS display (Fig. 6a), it is feature-rich to improve the clarity of presentation and ease of control for an operator besieged by information overload. The PPI is based on software provided by the CDK, which eases extendibility and provides for future enhancement. It takes up most of the screen space and shows geographic information, overlaid graphics, and symbols at the locations of known objects. Additionally, the ACIS has a primary and a secondary PPI. When invoked, the secondary PPI gives the operator a zoomed-in view of a tactical event (e.g., air intercept) while also maintaining a global long-range view in the primary PPI. If window overlap is a concern, either or both PPI windows can be resized and moved to any screen location. The layout of an ACIS display screen with two PPIs is shown in Fig. 6b. Significant PPI features include

- A display of geographic maps, radar video, special interest regions (e.g., op zones), graphics (e.g., grids), symbols showing the location and attributes of known objects (e.g., sensor “tracks”), text, and labels. The display is layered so that maps appear under filled zones that are under radar video which in turn is under text and symbology. This enhances the visibility of objects in the display.
- Enhanced map displays with coastlines, lakes, rivers, country and territorial boundaries, cities, airways and airfields, roads, and railroads (Fig. 7). Any of these can be selected to be on or off in either PPI using control panels that are provided by CDK. This

gives the operators the flexibility to tailor the map presentation to best suit their needs.

- A method for selecting or “hooking” a specific object using a point-and-click device to control an on-screen cursor. Advanced hooking features include a dynamic “pre-hook” readout for the object that the cursor currently points to and that would be hooked by a click. This readout can be positioned anywhere inside the PPI. The readout contains up to 10 lines of data

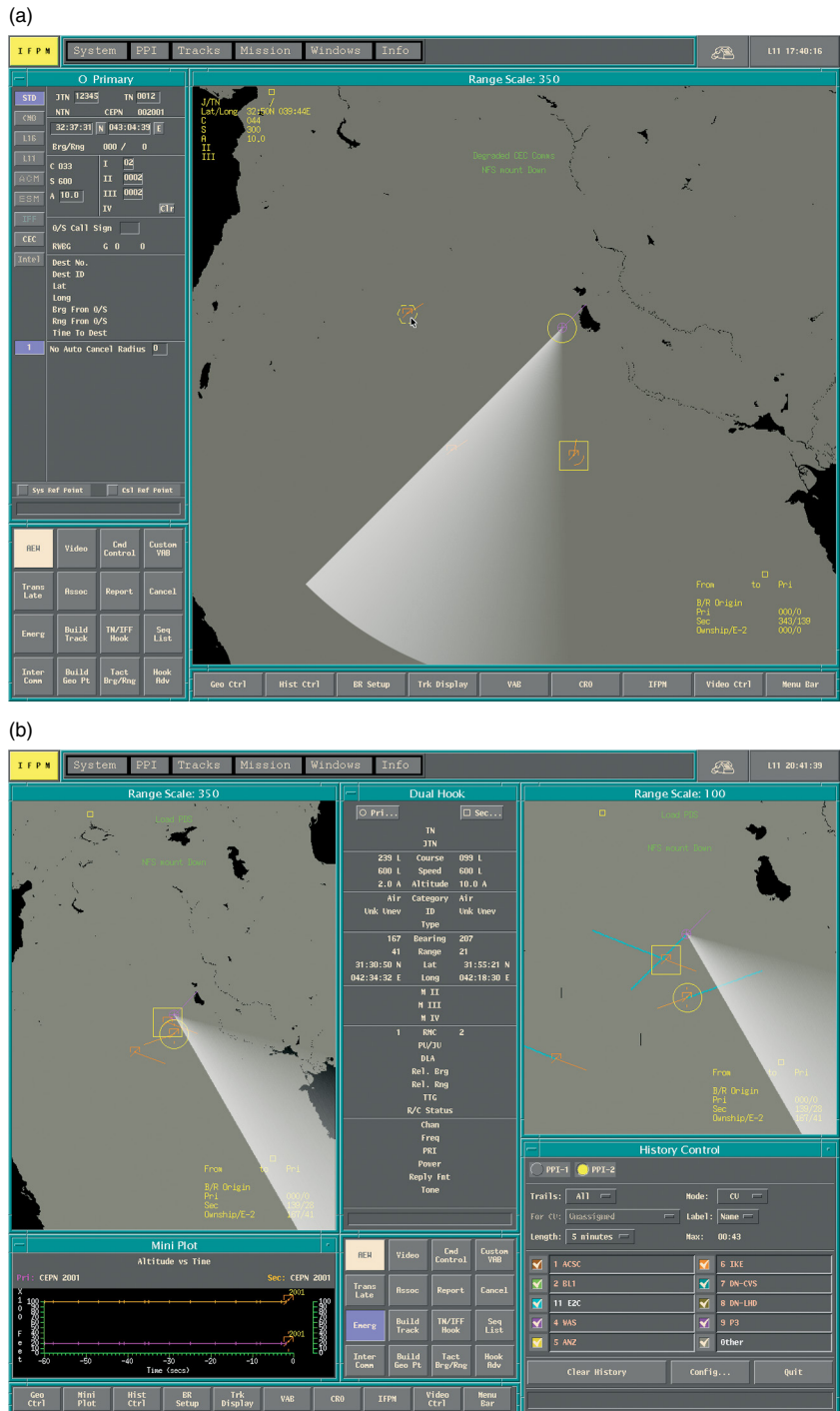


Figure 6. The ACIS display with a single PPI layout (a) and (b) two PPI windows with a customized layout at different ranges, each with its own scaled and clipped radar video.

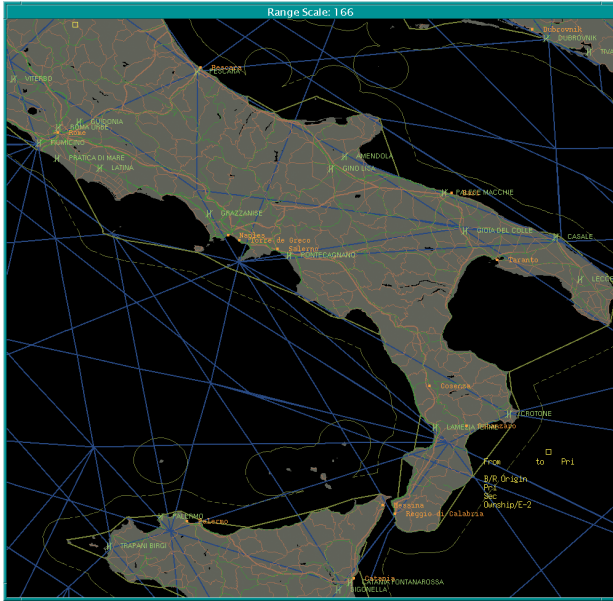


Figure 7. The ACIS can display a wide variety of geographic information on the PPI. This information can be used to aid the operator in determining locations and borders.

and changes instantaneously as the cursor moves within the PPI. This allows operators to quickly obtain information across groups of tracks without constantly clicking the pointer button. It also permits the accurate selection of a specific track out of a cluster. This feature was originally proposed for the Aegis display system by Osga,⁷ who called it “advanced hooking.” In addition, two hooks are available, a primary (circle) and a secondary (square) hook for paired association actions (such as assigning an air intercept) and extra information in a secondary CRO window.

- The use of color to improve object visibility and to encode special attributes. Battle group participants can be color-coded, and these colors are then used for associated pairings (such as engagements). The color intensity of any specific object type can be adjusted, e.g., to make grid lines dimmer or pairing lines brighter, to highlight some objects, and to suppress others. In addition, the interior of the Naval Tactical Display System’s track symbols can be color-filled by ID, which makes them stand out clearly against the background objects. Background colors for land and sea are subdued shades of gray to provide good contrast with overlaid graphics, radar video, and symbology. The intensity of the background can be adjusted by operators to their preferred visibility levels.
- The display of colored history trail dots behind a selected class of air tracks. These history trails can be color-coded by the type of sensor that detected the track at that point, information that is useful in a multisensor CEC net. The history trails can also be color-coded by ID, an operator-selectable option.

- Controls to customize the track display by filtering classes of objects to be displayed as small symbols or dots. This capability provides the operator with the ability to tailor the track display presentation to accentuate information of interest while reducing clutter. Incorporated in this filtering feature is a set of unconditionally displayable rules, which force high-interest or threatening objects to the operator’s attention, even if those objects have been reduced by the filtering controls.
- Passive tracks that are shown in several rings around the edge of the PPI in which no other objects are drawn, making this information clearly visible. If a specific passive track is hooked in its ring, then a history of associated bearing line positions is displayed in the central area of the PPI. The display of this information is a unique feature of the ACIS which provides increased display capability to the operator.
- Single-track alerts that are given by blinking the associated track symbol. When the track is hooked, the blinking stops and a pop-up information or action panel appears that gives selectable choices for actions that can be taken. This expedites an operator’s handling of alerts with minimal interference to other activities.

In addition to the PPI, other basic ingredients of the ACIS default display layout include the CRO window, a menu bar, a taskbar, a VAB panel, an in-flight performance monitor (IFPM) alert button, a time readout panel, and a teleconference alert button. Further, an operator can customize the screen layout (Fig. 6b) with specialized information and control panels, and can recall a saved layout as needed.

The E-2C community decided to design its CRO window to be more than a data readout panel. Although it has multiple selectable types of readouts, it additionally supports operator input and control by having editable fields (some with option menus) and specific control functions (using buttons and check boxes) for the currently hooked track. Thus, it also serves as the single-track control window.

The menu bar is located across the top of the screen and contains buttons labeled System, PPI, Tracks, Mission, Windows, and Info. Clicking on any of these elicits a pull-down menu listing specialized tools, and clicking on any tool name invokes a window implementing the tool. The pull-down PPI menu is a consistent feature on CDK-based platforms.

The taskbar is located across the bottom of the screen under the primary PPI. Any active tool window is dynamically assigned a button on the taskbar in a manner familiar to PC users. Then, any tool window can be minimized to clear space on the screen. However, an operator can instantaneously reinvoke the tool by clicking on its taskbar button.

The VAB is an array of buttons in a panel located at the bottom left corner of the screen. The VAB is similar in appearance to a calculator keypad; however, each button is specific to a unique ACIS function. The VAB allows the operator to quickly access functions that are most often used without the need to access the menu bar. In addition to the on-screen VAB, a hardware VAB keypad is located on the bullnose left of the keyboard. This keypad mimics the software functions so that an operator can focus on the display screen and simply press a hardware VAB button to perform an action. Any action taken is shown on the display by highlighting the corresponding software VAB key. This provides the operator with increased speed and the flexibility to perform operations without moving the mouse away from an area of interest.

The IFPM button, located at the top left corner of the screen, is used for monitoring system and subsystem alerts. When new alerts arrive, the IFPM button changes color (red, yellow, or green) according to the highest-priority unread alert received. When the operator wants to see the details about the alert, clicking on this button causes an IFPM readout panel to appear. Closing the panel changes it back to a button and clears the alert status color until the next new alert is received.

The time readout panel, located at the top right screen corner, shows the current clock time. It is configurable to select the source and format for the clock time. Clicking on the time button elicits a larger control panel for selecting the time readout parameters.

The teleconference alert button is at the top right of the screen beside the time readout panel. This button lights up when there is an incoming CEC teleconference request. Clicking on this button invokes a panel in which a real-time interactive discussion can be held with other battle group participants through the CEC network. Multiple participants can simultaneously be in any teleconference session, and there are 10 channels to support separate sessions. This tool works like the familiar chat capability available on the World Wide Web.

The layout and content of windows in the ACIS display can be tailored to an operator's preferences. Almost all windows and panels are movable and resizable, so an operator can tile the screen with the windows currently being used to support a mission task, as shown in Fig. 6b. A useful arrangement of windows can be saved using the layout tool and then quickly restored by name as needed. Additionally, as already noted, some panels can have customized controls or readouts specified by the operator. For example, the prehook CRO in the PPI window can contain up to 10 lines of data, which can be selected from a palette of over 40 data items. Similarly, one can have a custom VAB panel and customized object color settings, as well as others. A useful customization can be saved for later recall by applying a setup command. In fact, the contents of many control panels

can be saved and restored with the setup command. Furthermore, a collection of saved panel setups and a screen layout can be grouped and restored as a single entity with the Autoload tool.

The ACIS display has many information and control panels that support specialized mission tasks. These include the following:

- The CEC ID doctrine definition and management system
- An enhanced HookBy panel to hook tracks by an identifying parameter (such as a link number). Earlier queries can be easily recalled from option menus.
- A flight path management and real-time monitoring tool
- A timeline mission event-scheduling tool with reminders
- A miniplot panel that displays an altitude-versus-time plot for an air track. When a track is hooked, a history of its altitude is instantaneously displayed.
- A radar masking tool that shows terrain blockage for radar sensors. This tool can show coverage for all radars in a battle group.
- A VCR-like mission scenario recording panel (Fig. 8) for recording tracks and other information input to the ACIS during a mission or test event. This tool has instant replay and postmission playback capabilities.

These information and control panels enable a great deal of functionality to be packed into a small space on the ACIS display screen. The ACIS HMI was designed to give the E-2C operators maximum perception and control with simplified quick access to the most important and frequent operations through streamlining of the underlying HMI functions. The design of this HMI was performed by a Navy-selected design team that included representatives from all interested participants, i.e., a Navy design lead, E-2C operators, industry (Northrop Grumman), and the ACIS developers (APL and NAWCAD). It was understood by all that the economy and efficiency of the ACIS HMI was a prime factor. The final product is evidence of the outstanding effort the team put into this design.

Integrating Radar Video with Maps and Symbols

The ACIS features a radar scan sweep displayed on top of maps. Track symbols are then displayed on top of the radar sweep and maps (Fig. 6). Operators can see tracks forming from radar hits before they are digitally recognized by the MC tracking algorithms. In the ACIS, special "slant-range" Earth projection functions align track symbols with the underlying video and maps. Although some of the hits may be ignorable noise, this capability lets the operators form their own opinion about initial track formulation and track continuation during target maneuvers.

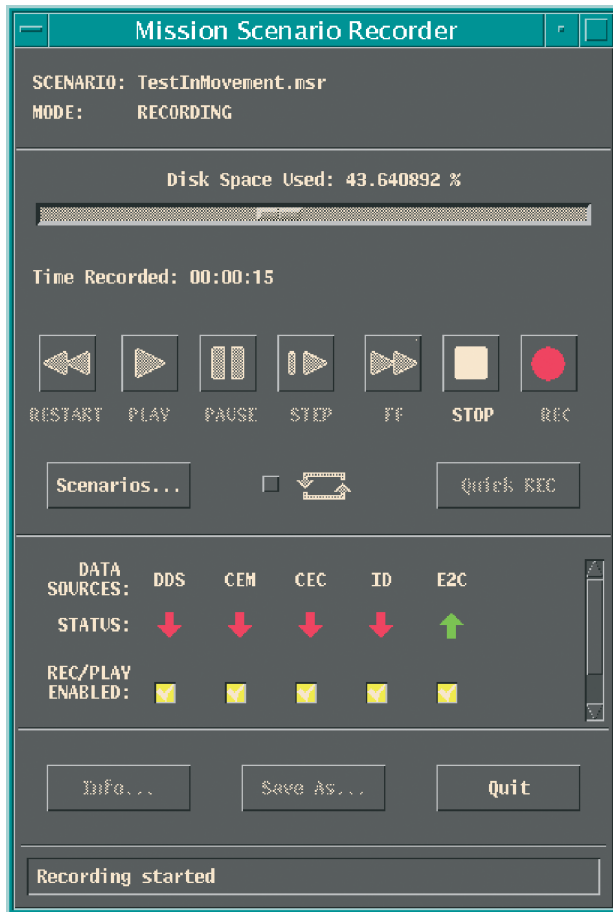


Figure 8. The Mission Scenario Recorder acts much like a VCR, recording and playing back data that are received by the ACIS display system.

The RIB and RSC boards provide the radar sweep. The RIB receives video input directly from the E-2C radar and IFF, which feeds directly into the RSC board. The RSC then projects a radar sweep image directly into the graphics board. Because radar video is interlaced directly into the graphics board, the CPU is free to perform other data processing.

As added capabilities, the radar scan board was upgraded to support two separate video sweep lines and also a color-blended radar sweep. Instead of a traditional one-color white radar sweep, color blending is done with the sweep and the underlying maps. For example, if the radar sweep is over a grayish land area, it will be a lighter shade, giving a smoother radar sweep. All of this is combined to give the operator greater situational awareness.

Combined Picture from Multiple Combat Sources

The E-2C's most demanding task is to collect data from an array of sensors and communications links and present all the potentially disparate information in a

single, coherent picture. These subsystems include the APS-145 radar, IFF, tactical digital information links (Link-4, Link-11, and Link-16), passive sensors, and CEC. It is the MC's function to interface with these subsystems, collecting and correlating data. The ACIS then serves as the critical user interface, allowing the operator to access the information collected and managed by the MC.

All sensor-related functions on the ACIS are organized into logical areas. Subsystem configuration and controls are grouped together under the System menu. General PPI-related functions can be found under the PPI menu. General track-related controls, such as track and geo-point establishment, can be found under the Tracks menu. Mission-related information and controls (including ID doctrine configuration) are found under the Mission menu. Specific information on each selected track is displayed in the CRO. In most cases, the CRO also allows many individual track attributes to be modified.

A specialized symbol set has been developed for the ACIS, which allows the operator to quickly distinguish the basic nature of a track by simply looking at its symbol in the PPI. If a particular track needs to be investigated, the operator hooks the track by simply pointing and clicking on its symbol. The CRO will update immediately to display the latest information on the track. The VAB panel will also update automatically to indicate additional properties and actions that can be performed on the hooked track.

After hooking a track, available information is immediately evident from the CRO, laid out in groups of "pages," with each group categorized by sensor or function. The availability of each page group is indicated clearly with a button, and an unavailable page has a grayed-out button. All tracks have a standard series of CRO pages containing basic track information, such as absolute and relative position, course, speed, and altitude. Additionally, aircraft controlled by the E-2C have a series of C2 CRO pages, and CEC network tracks have a series of CEC CRO pages available.

Control of the MC as a subsystem is performed through the ACIS. Controls are limited to functions such as resetting or shutting down the MC and clearing various portions of the MC's internal track file.

Radar controls are grouped together in a single window that contains a number of controls such as automatic mode selection, automatic channel selection, and rotodome speed. Similarly, IFF controls such as interrogation are also consolidated into a single window. The ACIS allows interrogation of Modes I-IV and C. Configuration of IFF interrogation sectors can also be performed in this window.

The E-2C uses a variety of tactical digital information links to exchange tactical information among members of the battle group and to provide C2

capability. All data link setup controls are managed on the ACIS through a single window. This window allows control over all basic Link-4, Link-11, and Link-16 functions (e.g., link reference points, track number limits, gridlock, track reporting, and link frequencies). Most other link functions, including C2, are handled directly through CRO and VAB controls.

The ACIS also displays alerts originating from these data links. The operator can quickly distinguish which track has an alert, hook the track to obtain more information on the alert, and immediately take action based on the alert.

The aircraft can be configured with one of two types of passive detection systems mentioned earlier: the PDS or ESM. The ALR-73 PDS is an older, more limited detection system which provides precision direction finding, passive ranging, and emitter threat ID. The newer ALQ-217 ESM system, manufactured by Lockheed Martin, offers significantly increased performance and reliability, as well as substantially reduced weight. Both subsystems are configured through a single window. The ACIS recognizes which system is available and configures this window accordingly.

One unique feature of the ACIS is the manner in which passive tracks are displayed. Passive tracks have a bearing but no range. These tracks are detected by the PDS or ESM subsystem and are displayed around the edge of the PPI in a series of rings, depending on the general passive track classification. This design reduces clutter in the PPI window significantly.

All CEC-related functions are logically grouped together on the ACIS. CEC tracks are displayed in the PPI much like local tracks. However, there are two basic categories of CEC tracks: MC-correlated and -uncorrelated tracks. MC-uncorrelated CEC tracks are displayed in the PPI with a unique track symbol modifier so that they may be quickly distinguished from other types of tracks. MC-correlated CEC tracks cannot be distinguished from other local tracks shown in the PPI since correlated CEC tracks are essentially local tracks with additional CEC data.

E-2C aircraft configured with CEC have an ID processor that provides the ability to automatically determine the identity of tracks using an ID doctrine, a set of parameters and attributes to determine a track's identity. The ACIS allows complete control over these doctrines, including the ability to create and manage them.

The ACIS provides integrated C2 from a single workstation. The basic C2 operations, consolidated into a set of related VAB functions, can be performed on any track reported over the tactical digital information links. Likewise, control can be passed among participants in the links.

CONCLUSION

The ACIS combat system display represents a major leap forward in operator situational awareness, providing the E-2C with a combined tactical picture using modern GUI technologies, standardized interfaces, and COTS products. The incorporation of a common GUI allows operators in the aircraft and operators throughout the battle group to interact with the display in a similar manner. This common interface, combined with a common tactical picture, allows the E-2C to effectively coordinate engagements and control the littoral battle space. The incorporation of standardized interfaces and protocols allows the ACIS to robustly communicate with other combat systems and easily incorporate additional systems. The use of COTS hardware and software dramatically decreases overall system cost and allows for upgrades as technologies progress. The result is an effective combat system that provides a consistent, combined tactical picture from multiple sources.

An early operational version of the ACIS and MC software has been deployed with VAW-117 in support of Operation Enduring Freedom. Initial reports from flight officers indicate a substantial improvement over the prior Group II systems. The upgraded E-2Cs flew over 200 combat sorties in support of mission operations.

Development continues on the ACIS display software at APL and NAWCAD, and is well into the fourth major developmental revision. On flight-test aircraft, the ACIS, MC, and CEC versions are undergoing testing. The full H2K system will be evaluated in a late 2002 technical evaluation and an early 2003 operational evaluation. After that, it will be officially deployed in the Fleet squadrons. The ACIS display and the concepts that it introduces will provide the Navy with a superior airborne C2 capability well into the 21st century.

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