Too Much of a Good Thing: A Discussion of the Excessive Advisories, Cautions, & Warnings in the E-2D Advanced Hawkeye

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***Abstract** - The E-2D Advanced Hawkeye is the Navy's most modern airborne early warning command and control platform. Projected threats necessitated significant upgrades to both the airframe and the mission systems of the E-2. One of the most notable design enhancements was the addition of a glass cockpit. Additionally, the Intercommunications System (ICS) sends to the aircrew an aural tone whenever any of the Advisory, Caution, and Warning System (ACAWS) lights is illuminated. Engineers attempting to integrate the mission systems information into the cockpit displays were faced with significant human factors issues, especially with the ACAWS. As a development program, this was to be expected, but the extent to which nuisance aural and visual ACAWS affected testing was surprising to the team. This paper focuses on the design philosophy behind the ACAWS and the unique human factors challenges the team encountered. Finally, lessons learned regarding ACAWS logic and implementation are discussed.*

Keywords: Advisory, Caution, Warning, Advanced Hawkeye, software.

1 Introduction

The E-2D Advanced Hawkeye (AHE) Aircraft (Figure 1) is an all-weather, high-wing, twin-engine, turboprop powered, carrier- and shore-based Airborne Early Warning (AEW) and Tactical Command and Control aircraft manufactured by Northrop Grumman Corporation. Distinguishing features of the aircraft are its horizontal 24-ft diameter rotodome and four vertical stabilizers.

The E-2D AHE is powered by two digitally controlled T56-A-427A engines, manufactured by Rolls-Royce Corporation (RRC), normally rated at 5,100 Indicated Shaft Horsepower (ISHP). The maximum rating can be increased to 5,450 ISHP with Automatic Power Reserve (APR) activated. The engines are fitted with digitally controlled Hamilton Sundstrand (HS) NP2000 8-bladed constant-speed, reversible propellers [1].

Figure 1. E-2D Advanced Hawkeye Aircraft.

The primary flight control surfaces (ailerons, elevators and rudders) are conventionally operated through mechanically interconnected control columns and rudder pedals from the pilot's and copilot's position. All the flight control surfaces are hydraulically actuated and irreversible. To simulate aerodynamic forces, feel springs are incorporated in each of the control systems.

1.1 General Changes from the E-2C

The E-2D aircraft was developed from the original E-2C Radar Modernization Program (RMP). As the scope was narrowed for the RMP, numerous hurdles and areas for technological advancement drove the program away from modifying existing E-2C aircraft and into producing new 21st century airframes, incorporating the latest in manufacturing processes and cutting-edge technology. Major changes to the E-2D aircraft are:

- New RADAR and Mission Computer
- Upgraded Radios and ICS
- Full Authority Digital Engine Control (FADEC) - type Propulsion System

- Increased Max Gross Weight / Structural Enhancements
- Increased Braking
- Glass cockpit with redundant digital avionics / Digital Air Data System

There are numerous changes to the E-2D aircraft; however, the scope of this paper is limited to a brief discussion on the E-2D digital avionics system, with a detailed focus on the ACAWS.

1.2 Digital Avionics / Architecture

The E-2D cockpit design centered around three 17-inch glass displays for primary flight information, navigation, engine monitoring, annunciations, and other mission functions. Controlling the digital avionics suite are two Avionics Flight Management Computers (AFMCs). These computers provide the primary and backup bus control for Navigation, Communication, Flight Management, Symbol Generation, and aural/visual ACAWS. Additionally, the E-2D now has a digital ICS, digital Backup Flight Displays, a Ground Proximity Warning System, a Crash Survivable Flight Incident Recording system, Embedded GPS and INS, and Category I ILS approach capability. The upgraded E-2D cockpit mitigates current obsolescence issues experienced by the E-2C fleet, while meeting current Communication Navigation Surveillance / Air Traffic Management (CNS/ATM) certification requirements.

2 ACAWS Overview

2.1 Legacy E-2 System

If you were to step into the cockpit of a current E-2C aircraft today, you might be surprised to see such an antiquated cockpit. Pilot alerts consist of a CAUTION display and ADVISORY display (as shown in Figure 2).

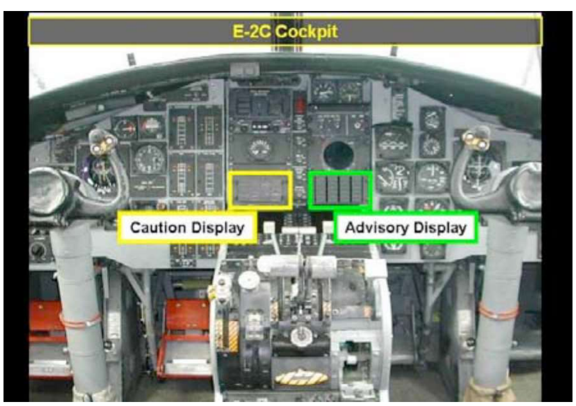


Figure 2. E-2C Cockpit.

There are no aural alerts available to the aircrew. Due to front panel real estate limitations, a total of 58 CAUTIONS and ADVISORIES are displayed. This area limitation drove a requirement to present broad engine category alerts, such as CHIP LIGHT. In the CHIP LIGHT example, the aircrew would have very limited information as to whether the CHIP LIGHT is for the Reduction Gear Box (RGB) section or the Engine section, until the problem continues to propagate. Additionally, if a CAUTION or ADVISORY is transient in nature (i.e., a light flickered), there is little chance the aircrew can identify which light momentarily illuminated.

2.2 Modern E-2 System

With the E-2D aircraft, incorporating glass displays and avionics flight management computers has allowed the designer to provide much more ACAW information to all of the aircrew. In comparison to the E-2C [2], the E-2D not only has 93 ACAWs displayed on the center display (see Figure 3), but also has over 200 ACAWs available to the aircrew (120 Advisories, 100 Cautions, and 7 Warnings).

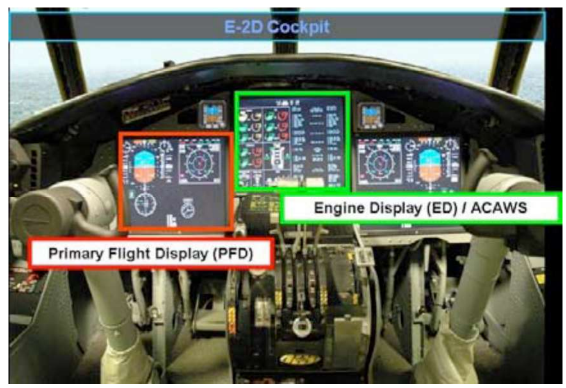


Figure 3. E-2D Cockpit.

When an ACAW is triggered, the aircrew can quickly gain situational awareness to the ACAW, as an aural tone is activated over the ICS and the visual ACAW is highlighted in reverse video for up to 10 seconds. If the ACAW remains after 10 seconds, the reverse video returns to normal video and the ACAW remains illuminated. Transient ACAWs are now latched for at least 3 seconds, thereby allowing the aircrew to quickly determine which ACAW momentarily illuminated.

When it comes to the presentation of ACAWs, the system designers settled on a layout that would provide aircrew with a quick reference of the alert based on color, grouping, and location on the center display. The standard RED, AMBER, and GREEN colors were used for WARNINGS, CAUTIONS, and ADVISORIES respectively. ACAWs that are not illuminated are shown on the display as GRAY text. Additionally, all the ACAWs are grouped such that WARNINGS are listed at the top of each group, followed by CAUTIONS, then ADVISORIES. Finally, each group has been prioritized and structured on the center display so that the highest priority items are at the top of the display, with the lowest priority at the bottom, as shown in Figure 4.

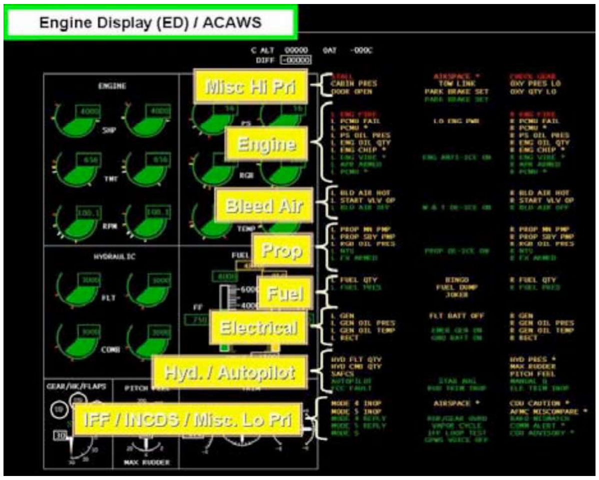


Figure 4. ACAWS Prioritization.

With over 200 ACAWs available to the aircrew, display real estate remained an issue with the as-implemented design. The solution required the concept of a "roll-up" ACAW. If an ACAW is illuminated on the center display, and that ACAW has more specific information, then an asterisk (*) will be displayed next to the ACAW. The aircrew can then use the Control Display Unit (CDU) to recall the CURRENT ACAW feature, which will show the specific nature of the ACAW.

An example of the ACAW Roll-Up feature is presented in Figure 5. In this example, the aircrew are alerted to a LEFT ENGINE CHIP CAUTION. Referring to the CDU "CURRENT ACAWS" page allows the aircrew to determine that the cause of this CAUTION is the LEFT RGB.

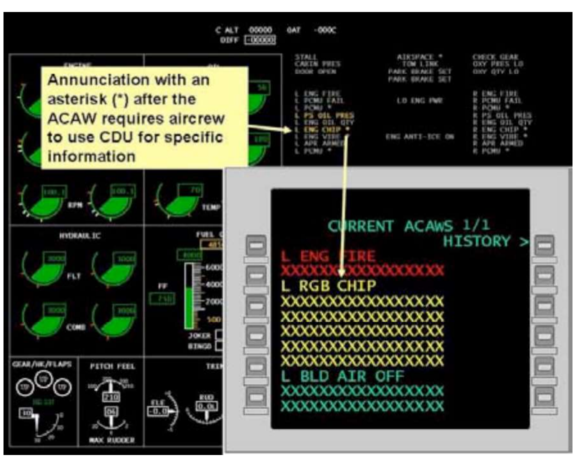


Figure 5. ACAWS Roll-up.

In addition to the CURRENT ACAWS, the aircrew can access a history of ACAWs. A list of the most recent 144 ACAWs are shown by type of ACAW (color code) with a DATE-TIME stamp. An illustration of this "ACAWS HISTORY" feature is shown in Figure 6.

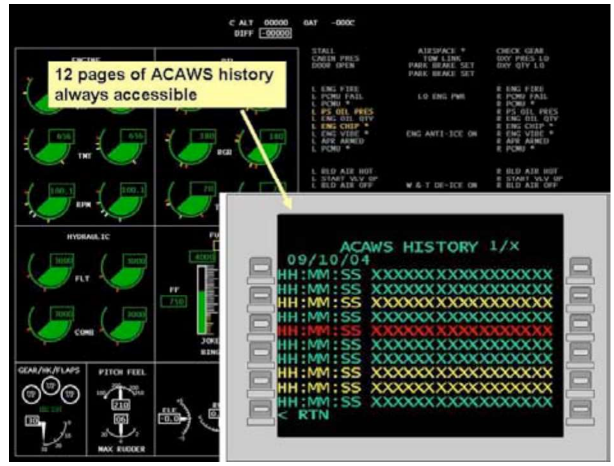


Figure 6. ACAWS History.

3 Too Much of a Good Thing

After approximately two years and over 1000 hours of ground and flight testing, "goods" and "others" were observed in regards to the E-2D ACAWs.

3.1 Successes in System Design and Integration (aka: the Goods)

There were a few advantages to the new E-2D ACAWS design. First, the aural tones immediately directed aircrew attention to the visual ACAW or impending failure or condition. The aircrew were significantly less likely to miss or neglect an ACAW when accompanied by an aural tone. Consequently, situational awareness (SA) was increased and the aircrew were continually provided the current state of the aircraft.

Moreover, if an ACAW was transient in nature (flickered), the light illuminated for 3 seconds before extinguishing. This feature allowed the aircrew to quickly determine which ACAW had momentarily illuminated and gave an early indication of an impending failure; a great improvement over the E-2C.

Altogether the E-2D ACAW system improved overall situational awareness in the cockpit as the aural tones and "ACAWS HISTORY" page were key to determining the aircraft's mission-ready state. The history page was available to all aircrew real-time: pre-flight, in-flight, and post-flight. The 12 pages of ACAW history were used during maintenance briefs/debriefs and post-flight data analysis which helped recreate flight conditions.

3.2 Hurdles in Design and Integration

Mostly the ACAWs worked as designed, but there were times when then system became "too much of a good thing" as the title of this paper suggests. In other words, the system sometimes told too much; or at other times did not tell the truth. As developmental testers there was an expectation to correct some ACAWs, but the extent to which ACAWs caused problems was surprising.

Some ACAWs were erroneous in nature meaning they triggered wrong or inaccurate information to the aircrew. Erroneous ACAWS, left unverified, could easily confuse the aircrew and force them to take the wrong action. Other ACAWs were nuisances meaning they were annoying and unpleasant to the point they interfered with normal flying tasks. The combination of the erroneous and nuisance annunciations significantly contributed to an overabundance of ACAWs illuminations and aural tones.

These excessive occurrences were observed since the earliest ground tests and continued for some time, even contributing to the early abort of the first E-2D flight in August 2007.

An interesting correlation existed between SA and pilot workload in-flight. As noted in the previous section, SA was instantly increased with the new ACAWS design, but that came with a price. Pilot workload was increased because extinguishing the aural tone required "punching out" (depressing) the Master Caution (MC) / Master Warning (MW) button to silence the aural tones.

3.3 Flight Test Specific Impacts

Inside the telemetry (TM) station the test conductors and engineers also faced challenges as a result of the excessive ACAWs. For cost and schedule purposes, an ACAW repeater was not developed for the telemetry station. A continuous hot-mike was used between the aircraft and the TM station, which meant that every aural ACAW (what we call a "deedle") was heard by the TM engineers. Quite frequently the deedle heard by the TM crew would lead to one of two things: intense focus on individual data charts or ignoring a potential issue and focusing on the system-under-test / test point.

Test efficiency was also negatively affected by the excessive ACAWs. The initiation of test points was frequently delayed as the deedles interfered with TM and aircraft communications. Inadvertent "knock-it-off" calls and "return-to-base" decisions were often the result of nuisance and erroneous ACAWs.

3.4 Aircrew Safety Impact

The impacts of the excessive ACAWS had four distinct impacts to the aircrew in that they were annoying, distracting, disrupting, and desensitizing.

- Some ACAWS were annoying in the sense that they were repetitive and there was no way to get rid of them. Many of the ACAWS in this category were manual switch actuations or other obvious items that did not require aural notification (i.e., parking brake).
- ACAWs were distracting in that attention was diverted either from critical operator tasks or at critical times.
- ACAWS were disrupting because they interfered with internal and external communications as the aural tones "stepped on" radio and ICS transmissions. Consequently, communications were missed with ATC, approach controllers, and the test conductor.
- The biggest safety risk was the likelihood of the aircrew becoming desensitized to the "deedles" and either not hearing/seeing the ACAW or even ignoring them.

From the normal seating position in the cockpit, pilot and copilot fingers rest upon the glare shield quite naturally and the repetitive nature of punching out the MC/MW led to habitual and almost "unconscious" resetting of the MC/MW sometimes without looking to see which ACAW illuminated.

3.5 Mission Impact

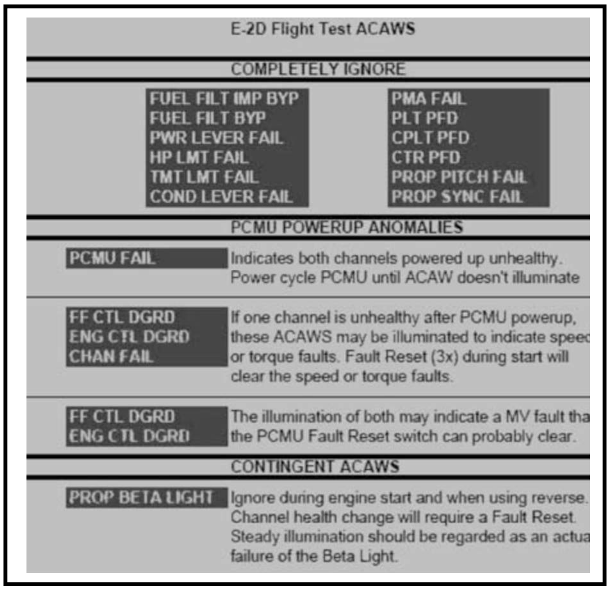
If fielded to the fleet in its original developmental condition the excessive ACAWs would present a severe hazard to the aircraft, the weapon system, and to personnel. Excessive nuisance ACAW indications will distract pilots from controlling the aircraft during high workload tasks, such as night carrier landings, and desensitize the aircrew from providing immediate response to actual critical alerts, or may cause unnecessary actions to be taken, resulting in potential loss of the aircraft and aircrew.

3.6 Program Risk Mitigation

The excessive ACAWs were certainly an issue to confront during testing, but instead of delaying the test program, the team had to find a way to continue. Certain risk mitigators had to be put in place to combat the negative effects of the excessive ACAWs. As a test team we really did not invent any new ways to improve our effectiveness, but rather used proven, time-tested risk mitigation methods and sound judgment to continue to safely test. We insured our briefs and debriefs were thorough and encouraged all involved to ask questions and seek answers to anything which may have been confusing.

Engineers and the test conductor in the telemetry station backed up the aircrew throughout all phases of flight in identifying those ACAWs which were either a nuisance in nature or indicating a false fault. Aircrew read boards were also used to convey important observances or techniques to combat ACAW fatigue.

Kneeboard cards were another effective tool for risk mitigation. Aircrew and engineers joined together to create quick guides that could be referenced anytime in flight. These guides were used to distinguish between those ACAWs that indicated true failures versus those ACAWs that were erroneous. An example of an actual kneeboard card used in the early stages of flight tests is shown in Figure 7.


E-2D Flight Test ACAWS

COMPLETELY IGNORE

FUEL FILT IMP BYP
FUEL FILT BYP
PWR LEVER FAIL
HP LMT FAIL
TMT LMT FAIL
COND LEVER FAIL

PMA FAIL
PLT PFD
CPLT PFD
CTR PFD
PROP PITCH FAIL
PROP SYNC FAIL

PCMU POWERUP ANOMALIES

PCMU FAIL — Indicates both channels powered up unhealthy. Power cycle PCMU until ACAW doesn't illuminate

FF CTL DGRD
ENG CTL DGRD
CHAN FAIL — If one channel is unhealthy after PCMU powerup, these ACAWS may be illuminated to indicate speec or torque faults. Fault Reset (3x) during start will clear the speed or torque faults.

FF CTL DGRD
ENG CTL DGRD — The illumination of both may indicate a MV fault tha the PCMU Fault Reset switch can probably clear.

CONTINGENT ACAWS

PROP BETA LIGHT — Ignore during engine start and when using reverse. Channel health change will require a Fault Reset. Steady illumination should be regarded as an actua failure of the Beta Light.

Figure 7. Actual Kneeboard Card.

4 Conclusions and Lessons Learned

4.1 System Design

Preliminary and Critical Design Reviews (PDRs / CDRs) are rudimentary steps in the evolution of a new system or platform and stakeholders, particularly the end user, will be present. From a system design point it is important to have the right mix of system users and experience at these events. The ACAWs design went through an extensive and rigorous process involving interface reviews at numerous working groups and safety meetings. The E-2D cockpit CDRs and PDRs had E-2 fleet, E-2 test, and single-seat warfare representatives in attendance; but test team consultation with multi-crew programs that had glass cockpit development experience, such as C-130J or V-22, may have alleviated some of our pains. Hence, our first lesson learned was the importance of discussing with other programs their lessons learned and mitigation schemes when developing their glass cockpits.

Furthermore, it is extremely important to ask the tough questions early on during the system design stage. Perhaps the most important question for the ACAWS would be, "Does everything require an alert, particularly an aural tone?" Tones sounded when actuating rudimentary switches in the cockpit that are utilized numerous times during the course of a flight and, in accordance with normal checklists, produced unintended consequences. For example, the parking brake lever and autofeather switches are manipulated numerous times during flight, and each manipulation is accompanied by an annoying and disrupting advisory tone. Thus, our second lesson learned is the realization that just because the system has the capacity to tell the aircrew everything, the system can easily give the aircrew too much information.

We started with the baseline of the E-2C ACAWS then modified that design to meet E-2D requirements which was a good approach and sound starting point. But it is important to be wary of the "give me everything now" expectation, where the ACAWS is designed to tell the operator everything that is wrong with systems that are not fully mature themselves (i.e., the propulsion control and navigation systems).

4.2 Planning & Execution

In terms of planning and execution, there was no substitute for sound knowledge of the aircraft and its complex systems. This lesson learned applied to both the aircrew and engineers as events occur too fast in the aircraft to sort nuisance ACAWs from meaningful ACAWs.

The preflight brief was an important place to iron out complicated details prior to the test event. We would have been wise to discuss the expected ACAWs for each test point during the preflight brief. Another important item to highlight during the preflight brief was crew duties, specifically identifying who would fly and who would troubleshoot during critical phases of flight. Highlighting aircrew/test team duties in accordance with sound Crew Resource Management (CRM) principles would have helped make the cockpit easier to manage.

Our TM trailer did not have an ACAWS repeater which meant the engineers had no way of knowing which ACAWS had illuminated unless it was verbally repeated from the cockpit. In flight, having the copilot verbally repeat the illuminated ACAW as it appeared would have increased the SA of the aircrew and the engineers in the TM trailer. Interestingly enough, calling out the particular ACAW is also a risk mitigation and hedge against becoming desensitized and reacting with fast hands because the pilot has to allow that extra moment to find and call out the illuminated ACAW.

4.3 Fixing the Issues

A significant enhancement of the ACAWS was the history feature which was crucial to in-flight SA and post-flight troubleshooting. We recommend including this feature in all future ACAW designs and for implementing in all platforms across the defense spectrum.

It is important to be flexible enough to implement work-arounds for continued program execution. No one software drop or script is going to give the 100% solution to the problems.

But while being flexible, it is also important to remain disciplined on implementation. We used the "roll-up ACAWS" due to real-estate limitations on the cockpit Primary Flight Displays (PFDs) but every now and then we had to stop and ask, "*Is all of this information really necessary?*"

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References

[1] NAVAIR 01-E2AHE-1, Draft NATOPS Flight Manual Navy Model E-2D Advanced Hawkeye (AA-1 and AA-2 Only), of 15 Jul 2007.

[2] NAVAIR 01-E2AAF-1, NATOPS Flight Manual Navy Model E-2C Aircraft, of 1 Sep 2006.