History of BGAAWC/FACT: Knitting the Battle Force for Air Defense

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Long before such terms as "system-of-systems engineering," "net-centric warfare," and "interoperability" became part of the lexicon of Navy air defense, APL was the Technical Direction Agent for an exploratory development program, the Battle Group Anti-Air Warfare Coordination (BGAAWC), later renamed Force AAW Coordination Technology (FACT). This program has continued since 1977 and has spun off such well-known programs as the Cooperative Engagement Capability and the Area Air Defense Commander capability. A number of significant innovations also have stemmed from this program that significantly contributed to "knitting" the battle force toward a unified, mutually supportive, cohesive air defense system.

INTRODUCTION

The need for coordinated air defense in depth goes back to World War II, where kamikaze attack aircraft were directed at our Pacific Theater naval forces. Even though the proximity fuze, developed by APL, greatly improved the defensive capabilities of that time, increased intercept range was needed to extend the depth of fire and handle large numbers of attackers.

With APL's role in developing the 3T-series (Talos/ Terrier/Tartar) ship-to-air missiles and then leading the effort to integrate them with search radars and weapons control, the problem became one of coordinating ships with overlapping anti-air warfare (AAW) ranges. With the advent of the Naval Tactical Data System (NTDS) and Link-11, the rudiments of coordinated air defense became a reality in early 1960. Still, variable capabilities in detection and tracking of enemy aircraft, and later anti-ship missiles, as well as manual implementation in coordinated defense, required further advances in all areas (detect, control, and engage). These threats necessitated more AAW automation as embodied in the Terrier/Tartar SYS-1 and -2 and Aegis[1,2] advanced air defense systems.

As these developments were anticipated in the mid-1970s, it was predicted that automation would cause a much larger coordination problem because of the much faster and higher-capacity systems. Initial concepts developed by APL anticipated solutions to this problem once the SYS and Aegis systems were fielded in the early 1980s. (The first, and more detailed, story of projected technology available for air defense developments at that time was presented by A. R. Eaton to the Joint AIA, A-AOA Tactical Missile Meeting in March 1973.[3] This was later published as an APL technical report.) Further analysis by APL revealed that major automations

had to be made to the tactical digital information links (TADILs) and other elements of the combat systems to provide the requisite coordination of the new generation of ship air defense systems. As a result, a program to develop the technologies to knit the elements of force air defense was needed. The effort to do this was started in 1977 and was called Battle Group Anti-Air Warfare Coordination (BGAAWC). Although it was recognized that all military air defense systems in a given area must be integrated as an amalgamated system for maximum effectiveness, the initial work dealt only with Navy surface and air-air defense systems.

After award of the Aegis development contract to RCA (now Lockheed Martin), several factors came together during the 1970s that resulted in the BGAAWC program, which by definition was to work on and solve Navy battle group air defense coordination problems. The factors leading to this program included the following:

- Projected Aegis performance gave promise of a capability to provide superior radar detection and tracking capability in its field of coverage that could be used by all elements in the battle group.
- Fleet experiences with the 3T weapon systems continued to illuminate severe ship interoperability problems with NTDS Link-11, resulting in below-acceptable performance, though vastly improved from that in the 1960s. Fleet exercises still experienced many blue-on-blue (friend-on-friend) engagements, and non-Aegis Combat System speed, capacity, and data link reporting fidelity was not adequate.
- Vastly improved technology—displays, computer processing, automation, and miniaturization—was available but not yet exploited for fully coordinated defenses.
- Studies by APL and others all concluded that if the air defense assets in a battle group could be "coordinated," the resulting effectiveness would be significantly improved. The critical assumptions used in these studies were perfect target detection and track, perfect gridlock, and adequate data communications capacity. These assumptions were not realized capabilities, and the technology to make them a reality needed to be developed.

Based on these factors, farsighted people at APL and in the Navy recognized that Aegis could be a force multiplier for the battle group if its superior detection and tracking data could be distributed and its advanced firepower could be coordinated with other Aegis and Terrier/Tartar ships. It was envisioned that the Aegis single-ship superior capability could coordinate weapon-to-target pairing of the entire battle group. The Aegis Defense Systems Acquisition Review Council in the early 1970s directed that this concept be pursued.

During this period, APL was functioning as Technical Advisor to the Navy while continuing ongoing studies and developments to improve coordination of non-Aegis ships until Aegis became operational, at which time Aegis would become the centerpiece for air defense improvements. Data links, displays, and other elements were being defined to achieve the leverage needed to make Aegis the force multiplier envisioned. In 1977, APL was designated the Technical Direction Agent for the Task Force AAW Coordination program, later the BGAAWC program and subsequently the Force AAW Coordination Technology program (FACT). (The change from TFAAWC to BGAAWC was a result of a Navy terminology change from Task Force to Battle Group; the change from BGAAWC to FACT was the result of Congressional direction.) A plan was developed that envisioned multiple phases. The principal concepts were to develop and employ, synergistically, multiple battle group resources to counter increasingly sophisticated threats through increasingly sophisticated coordinated engagement techniques, as shown in Fig. 1. Aegis was to be the linchpin of these sophisticated techniques.

The intent of the BGAAWC task was to extend Aegis Combat System track data and provide coordination to all elements of the battle group to maximize battle force air defense effectiveness. This required many innovative improvements to be developed. The mission of the BGAAWC program was to develop and demonstrate improved force air defense effectiveness through coordination and knitting of combatant combat systems—Aegis, Terrier, and Tartar.
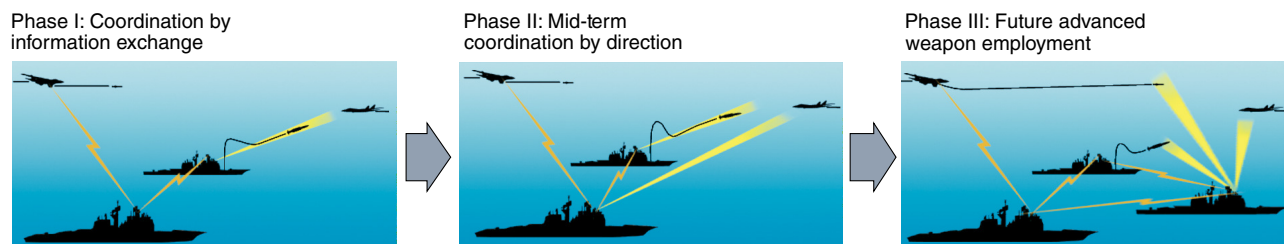

Figure 1. Coordinated engagement techniques.

BGAAWC/FACT

Overview

BGAAWC, and later the FACT program, has provided a significant number of innovations leading to a more integrated battle force. The following sections describe these contributions. This section summarizes the accomplishments and spin-off programs in the context of the battle group as a system.

From the very beginning, the needed capabilities to be incorporated into a battle force were identified as pyramidal stair steps of foundation building blocks. At the same time, the future advanced concepts vision was presented and treated as a road map. Figure 2 is a collage of these key program and technical elements. At the left of the figure are the steps in foundational order according to the air defense precepts of detect, control, and engage. The listed functional capabilities were identified and worked in order so that those required as a prerequisite for another function would be developed first. Thus, sensor improvements (e.g., automating the Fleet mainstay AN/SPS-48 radar of the 1970s and early 1980s) were prerequisite to distribution of high-quality tracks, the next function up the stairway (track data distribution/connectivity), and so on. The road-mapped goals identified from the beginning are shown at the top of Fig. 2, labeled "Remote track launch on search," "Remote magazine launch," etc. It was recognized, based on force air defense studies and simulations, that the ability of the combatants of the force to contribute to a force-wide defense in a highly integrated manner would provide the best value for the Fleet investment. The BGAAWC/FACT approach, from the beginning, has therefore been to develop capabilities that could be inserted and incorporated into evolving combat systems and linked to increase their inherent value and interoperability with the force.

A key point is that the BGAAWC/FACT program, over more than 20 years, has contributed in major ways to integrated battle force air and missile defense. Another key point is that this legacy is continuing to meet a need as each generation of battle force technologies, capabilities, and automation requires a commensurate evolution in force-wide capabilities to ensure their synergistic coordination and interoperability.

The next sections discuss many of the BGAAWC/FACT developments.

Data Links and "Dial-A-TQ"

The advent of digital data processing capabilities of the NTDS and TADILs, such as TADIL A (Link-11) and TADIL C (Link-4A), was the starting point for achieving more effective battle group air defense. (Link-11 in the battle group has provided tactical data connectivity between ships and airborne early warning aircraft; Link-4A has provided tactical data connectivity among fighter aircraft, controlling ships, and airborne early warning aircraft.) Mutual support within the battle group was accommodated within the design of Link-11. Link-11 accommodates capabilities such as mutual tracking, which is fundamental to synergistic battle group radar tracking, and the maintenance of radar track continuity. Within a Link-11 network, the unit that maintains the best quality of a radar track will report that track (position, heading, speed, altitude, identification, and other supporting data) to all other network participants. If the quality of a track report (i.e., its likely accuracy and its longevity) is reduced and another network participant has better track quality (TQ), that unit assumes responsibility for reporting that track to others within the network. This feature can not only significantly improve the continuity of a track but also stabilize the track number, track identification, and other vital data. Link-11 command and control capabilities and other functionality were the foundation for mutually supportive force operations.

The NTDS Link-11 protocol was adequate until Aegis joined the Fleet in 1983. The full use of the Aegis SPY-1A radar (more accurate tracking and faster track update) by the battle group was constrained by the NTDS Link-11 reporting protocol. This protocol established that track generation and reporting be in accordance with seven TQ levels, depending on the frequency of the radar updates and on who first detected and tracked the target. The protocol was established for rotating radars and was immediately obsolete when Aegis
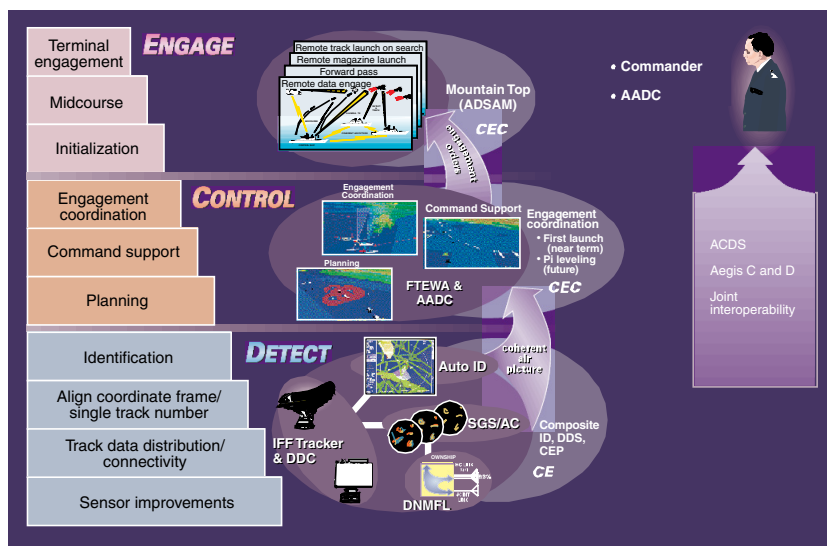

Figure 2. Battle Force AAW Coordination Technology plan and developments.

joined the Fleet. This obsolescence was because the first ship detecting and reporting a target would retain this responsibility until the quality of its track was decremented by 2 and another ship had a TQ of 2 higher, or the original unit dropped the track. The quality of the radar track was *not* considered in this protocol. Unfortunately, unless Aegis was the first to detect, track, and report (often a function of ship location), it was locked out and the battle group lost the benefit of its superior capability and timely reports until the TQ of the first reporter decremented by 2.

The Laboratory recommended, and the Navy approved, the implementation of a capability to select the maximum TQ for tracks reported by each TADIL participating unit. This capability was called "Dial-A-TQ" and was introduced within the air defense systems of all major combatants. Dial-A-TQ had the benefit of controlling reporting responsibility of mutual Link-11 tracks within the battle group. This capability can be used to preempt the reporting of mutual tracks by less-capable units, thereby ensuring that the most accurate tracking data are available on TADIL networks. Dial-A-TQ can be enabled to permit a single unit to use track-quality TQ 7, with the remaining Link participants dialed to TQ 5 or less, or it can be employed in different combinations to ensure that a selected set of units is assured Link reporting responsibility of mutual tracks within the battle group. Today, Dial-A-TQ is most often used to bias track reporting to the reference unit to enable alignment of the force to a common coordinate frame (called "gridlock," discussed later in this article).

Detection Data Converter for the AN/SPS-48C Radar

Fundamental to mutual support within the battle group is the capability to perform synergistic radar tracking of each aircraft or missile by all units participating within the TADIL network. To accomplish this and to counter the threat, rapid reaction by each participating unit is necessary. Essential to rapid reaction is the capability to perform fully automatic radar detection and tracking with a low and well-regulated false track rate.

Until 1983, the Navy's principal surveillance and midcourse guidance fire control radar, the AN/SPS-48C, required significant operator intervention to establish and maintain radar tracks. To reduce the probability of promoting false tracks from weather, land clutter, and various forms of radio-frequency interference, the radar was often desensitized by the operator. The trade-off problem with desensitization was so acute that

some threat aircraft and missiles would be undetected, as validated during numerous battle group training exercises.

To improve ship radar performance, the Laboratory had previously developed and demonstrated improved signal processing and automatic detection and tracking capabilities that changed the way in which radar was used by the ship and the battle group. This development evolved into the AN/SYS-1, which was integrated with the AN/SPS-52 and AN/SPS-40 radars and with the Junior Participant Tactical Data System aboard USS *Towers* class guided missile destroyers. Through the BGAAWC program the automatic tracking capability was modified and coupled to a signal processor specially developed by the Laboratory for the AN/SPS-48C radar. This development became the AN/SPS-48C Detection Data Converter (DDC).

The AN/SPS-48C DDC automatic detection and tracking system reduced a large quantity of radar data developed at high sensitivities needed for detecting threats to a relatively small number of valid target information in real time. Figure 3 illustrates an example of the DDC data flow that may occur under severe environmental conditions with 100 to 200 valid air tracks.

The analog-to-digital conversion in the DDC signal processor could produce 20 million detection opportunities per 360° scan of the radar antenna. In a typical dense environment, adaptive thresholding reduced this to about 4000 raw radar hits per scan. Additional processing rejected radar hits (i.e., echoes) that are a result of various interference sources or that do not spatially correlate with other hits. About 1200 radar hits are sent to the DDC centroid processor. The centroid processor combines adjacent radar hits into radar "contacts" and rejects contacts that do not represent true targets, producing about 900 radar contacts at the input of the DDC Tracker.

The DDC Tracker uses processes known as "activity control," "clutter point tracking," and "controlled track promotion" to eliminate remaining false centroids, initiate new target tracks, and update existing tracks. The overall process gives excellent target sensitivity while simultaneously controlling false tracks.

The DDC revolutionized the radar surveillance capabilities of the battle group. Totally unaided by operator
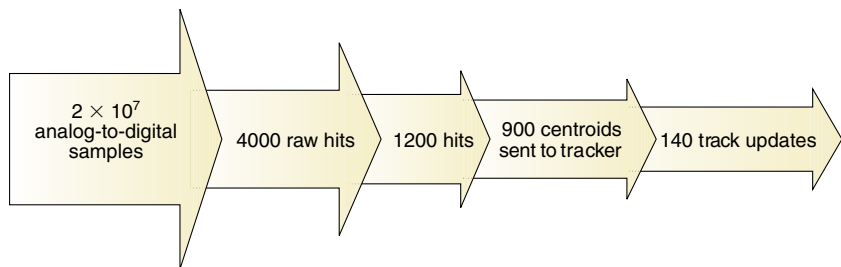
2×10^7 analog-to-digital samples → 4000 raw hits → 1200 hits → 900 centroids sent to tracker → 140 track updates

Figure 3. Reduction of track data.

manipulation of radar controls, the DDC reliably supports detection and tracking of aircraft and missiles throughout the volume of AN/SPS-48C radar coverage. The steady-state false track rate of the DDC was measured at one track, regardless of the track population, which can be 300 or more tracks. Further, the advanced signal processing capabilities eliminated the need for environmental control techniques, such as sensitivity time control, thus significantly increasing radar detection sensitivity. Figure 4 depicts radar detections and tracking before and after DDC processing.

The DDC technology was installed as a field modification to all shipboard AN/SPS-48C radars throughout the Navy in the 1980s. Laboratory-developed DDC technology was transitioned to ITT Corp., the AN/SPS-48 manufacturer, and to Navy in-service engineering organizations. Subsequently, the Navy and ITT instrumented all AN/SPS-48 radar-equipped ships with the DDC. The DDC Tracker was fully interoperable and was controlled by the ship's NTDS, and today by the successor to the DDC and NTDS, the Advanced Combat Direction System (ACDS) and the AN/SYS-2 Integrated Automatic Detection and Tracker System.

With the reliability of AN/SPS-48C DDC radar tracking and the revolutionary capabilities provided by the newly introduced AN/SPY-IA radar in USS *Ticonderoga* (CG 47) in 1983, the foundation was laid to enable other stable track-dependent innovations to be pursued.

Technology and lessons learned from developing SYS and DDC were later used as the foundation for tracking within the Cooperative Engagement Capability (CEC).[4]

Gridlock and Automatic Track Correlation

Reliable automatic radar detection and tracking, provided by the AN/SPS-48C DDC (and now also AN/SPS-48E) and the Aegis air defense system, coupled with mutual tracking capabilities made available by Link-11, greatly improved the potential to conduct synergistic air defense operations throughout the battle group. However, in the 1980s, ship and aircraft navigation was only accurate to within a few miles of the true location, and rotating radars were often misaligned relative to north; these inaccuracies were also exhibited by airborne early warning aircraft.

When there were disagreements among Link-11 participants as to their geographic locations and/or disagreements in radar azimuth alignment, the ability to share air tracks and to develop common track numbers of threats to support coordination was limited. In this case, instead of units mutually supporting the maintenance of radar tracks, units interacting via the TADIL would, on occasion, produce multiple tracks for each aircraft or missile, thereby confusing the battle group tactical picture. Figure 5a depicts the result of misalignment caused by navigational errors, and Fig. 5b shows the result of misalignment caused by radar azimuth differences. In practice, both navigation and azimuth misalignments were present in the radar track data exchanged via Link-11. To enable high-quality mutual tracking throughout the battle group, a mechanism was needed to automatically and accurately correct for navigational and radar azimuth misalignments between battle group participants.

The concept of all units aligning their reference coordinates to a single, central unit, enabling a single coordinate frame, was crudely practiced with the advent of radar and the ability to exchange track reports (verbally during World War II). This loosely rectified, relative-alignment mechanism, called gridlock, generally worked well when the maximum defense range was a few thousand yards. However, with the introduction of long-range automatic detection and tracking and missile engagements, coupled with the need to effectively manage the battle while minimizing the probability of fratricide throughout the expanded battlespace, the need to reliably achieve accurate gridlock became paramount.

Precision gridlock, relative to a single reference unit (GRU), is essential to achieve correct automatic track correlations (correlating two tracks that represent the same vehicle), while minimizing false track correlations (incorrectly correlating tracks that represent two different vehicles), within dense track populations of a battle group and the surrounding battlespace. The required gridlock alignment cannot be achieved and
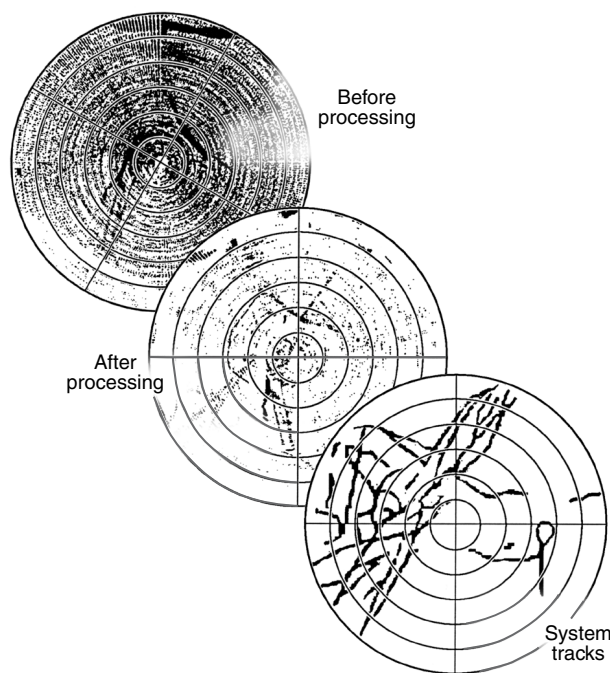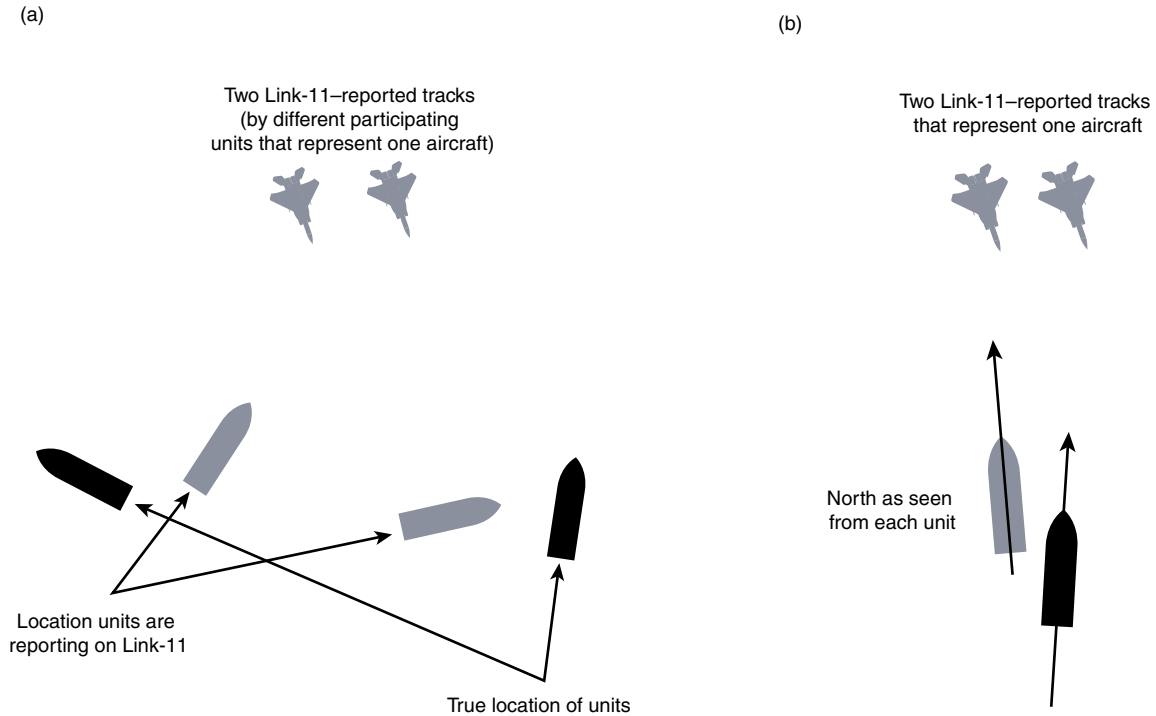

Figure 4. DDC processing.

(a)

(b)

Two Link-11–reported tracks
(by different participating
units that represent one aircraft)

Two Link-11–reported tracks
that represent one aircraft

North as seen
from each unit

Location units are
reporting on Link-11

True location of units

Figure 5. Gridlock misalignment caused by (a) unit navigational errors and (b) unit azimuth misalignment.

maintained by coarse operator-entered translation and rotation biases. Rather, to enable adequate performance, gridlock must be achieved to within the combined measurement accuracy of local and reference radar tracks. The complexity of the computation needed to achieve the required alignment to support high-confidence automatic correlation and to produce the synergistic integrated track drove the development of an automatic gridlocking capability. To solve this problem, the Laboratory developed the Shipboard Gridlock System with Automatic Correlation (SGS/AC).

SGS/AC is a computer program that receives local automatic three-dimensional radar tracks, receives remote tracks from TADIL participants, interfaces with the local air defense system, and is controlled from within the air defense system. SGS/AC can rapidly perform automatic gridlock to within the combined measurement error of the tracks reported by the GRU and local radar tracking. It performs automatic track correlation to a measured performance of ≥98% correct correlation and <1% false correlation, supporting a high-confidence tactical air picture.

Most precision gridlocking concepts of estimating alignment corrections among track data for two or more units depend on identifying mutual tracks by the unit to be aligned and the gridlock reference site. Without gridlock alignment, identifying such mutual tracks is a problem. SGS/AC employs a coarse bias estimation (CBE) algorithm designed to solve this problem by generating a cross correlation between local and GRU air tracks. CBE is a robust algorithm capable of accommodating even extreme translation and rotation misalignments. It rapidly produces a solution that is sufficiently accurate to support processing to identify mutual tracks needed to start a more precise Kalman filter algorithm. The Kalman filter provides precise gridlock corrections, including rate terms for aircraft GRUs such as an airborne early warning aircraft, which are refined and generally very stable. (The formalism for the Kalman filter design is also quite general and easily adaptable and extensible to new bias sources. The CBE approach, however, is heuristic and computational intense and so is normally only applicable to a few bias sources.) The CBE and Kalman filter operate in tandem, the CBE checking to ensure that the Kalman filter has not drifted from a valid solution, particularly when only a few mutual tracks are available.

After gridlock is achieved, the automatic track correlation process is activated to resolve multiple tracks in making a single track to represent each aircraft or missile using standard TADIL protocol. The automatic track correlation process is completed by intercomputer communications with the air defense system to ensure synchronization of databases and to ensure that recommended candidates are eligible for correlation, based on activities within the air defense system.

Figure 6a shows the track picture between two battle group units (an aircraft carrier and an E-2C aircraft) before gridlock, Fig. 6b shows the track picture generated by these units after automatic gridlock by SGS/AC,

and Fig. 6c shows the air track picture after automatic correlation by SGS/AC.

### Introducing the AN/SPS-48C DDC and SGS/AC into the Fleet

The demonstrated capability of the AN/SPS-48C DDC and SGS/AC resulted in demands from the Fleet to immediately install these capabilities within all deploying battle groups. Two approaches were authorized by the Navy to bring near-term capability into the Fleet: (1) transfer the Laboratory-developed technology to the Navy and to industry for production and (2) build additional prototype DDC and SGS/AC systems and deploy these systems, until production systems were built, in a pool that was to be rotated among deploying battle groups.

The DDC technology handoff to industry and the Navy was accomplished by the Laboratory assisting the AN/SPS-48 radar manufacturer and the Navy's In-Service Engineer in the design of modifications to the AN/SPS-48 to accommodate the new DDC technology. SGS/AC technology handoff was accomplished by transferring SGS/AC computer programs to the Navy's In-Service Engineer for operation within the Navy's AN/UYK-20 computer. The Navy embarked on a detailed development, test and evaluation, and training program to make these capabilities a standard part of ship combat systems. The DDC field modification to the AN/SPS-48 radar was installed in more than 60 radar sets within the Fleet and training facilities. SGS/AC has been installed in more than 70 ships and is currently a part of all new-construction Aegis destroyers.

To accomplish the mission prior to production, the Laboratory built a rotating pool consisting of eight AN/SPS-48 DDC and eight SGS/AC systems for deployment, four for the deploying battle group and four for the battle group that was training in preparation for deployment. The ships programmed for DDC and SGS/AC installations were AN/SPS-48 radar-equipped guided missile cruisers, guided missile de-stroyers, and aircraft carriers. The DDC and SGS/AC rotating pool prototype systems were installed over 7 years in 17 deploying battle groups (61 ships) until the Fleet was sufficiently equipped with production systems. In support of the DDC and SGS/AC rotating pool deployments, the Laboratory performed all systems installations and conducted maintenance and operations training for shipboard personnel.

The DDC and SGS/AC rotating pool capabilities significantly improved battle group operations by dramatically increasing the ability to achieve operational synergism between air defense units,
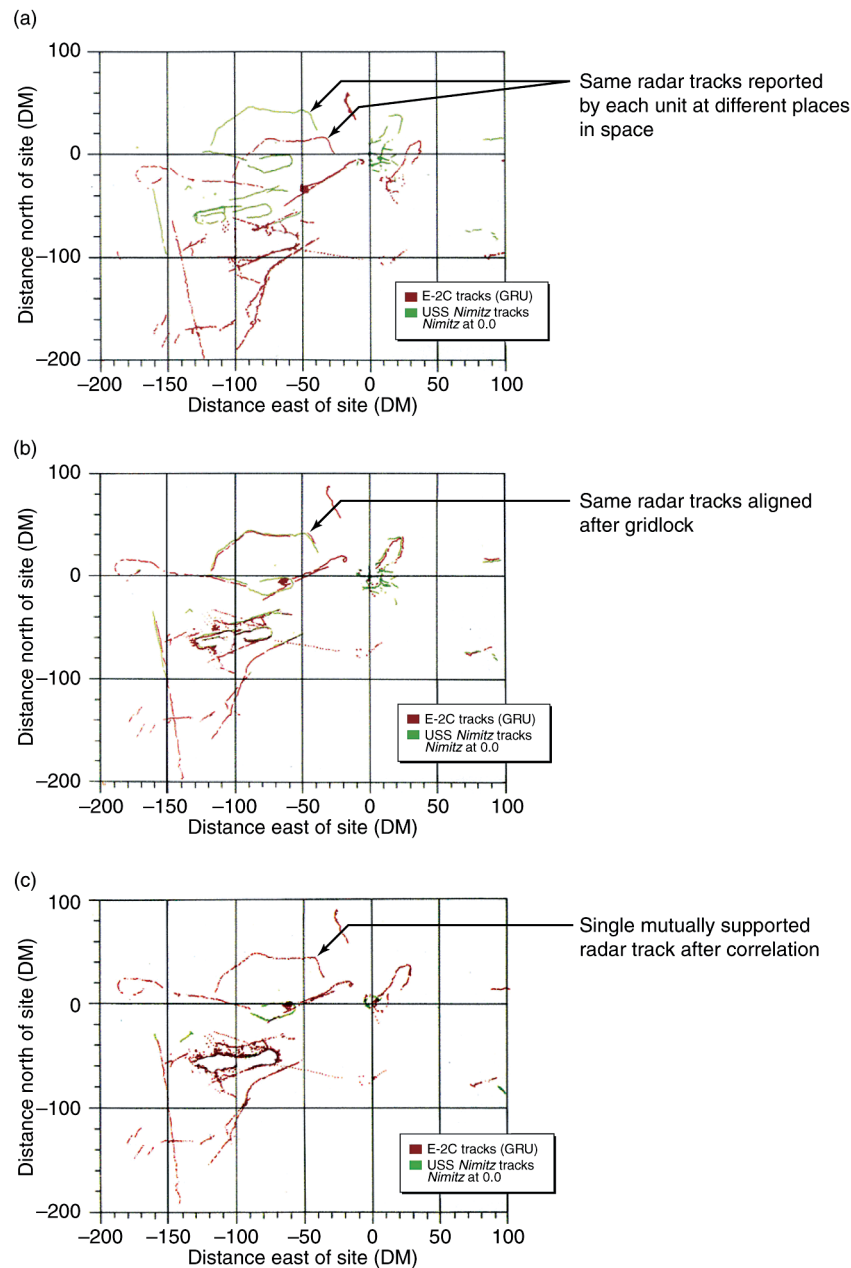
Figure 6. Two battle group units (a) before gridlock, (b) after automatic gridlock, and (c) after automatic correlation (DM = data miles).

providing the effect of force multiplication equivalent to more than the sum of parts, and eased the integration of the new Aegis capability into the Fleet.

Laboratory Afloat

In addition to satisfying emergent Fleet needs, the AN/SPS-48 DDC and SGS/AC rotating pool provided the environment to establish a "laboratory afloat." With the prototype systems, APL and the Navy were able to evaluate systems performance in complex operational conditions, including operations within hostile environments. Many lessons were learned and improvements were made to the DDC and SGS/AC capabilities. Moreover, many APL engineers became knowledgeable about battle group air defense engineering issues. This exposure allowed APL scientists and engineers to become intimately familiar with ship and battle group systems functioning in operational environments. The resultant familiarity set the stage for a much better understanding of the BGAAWC program mission. It provided the setting to learn about and understand battle group capabilities and deficiencies and served as the catalyst that led to the germination of sound ideas and resultant developments for improving battle group capabilities. Many future BGAAWC developments came from the experiences and subsequent warfighting understanding gained during the deployment of capabilities such as the AN/SPS-48 DDC and SGS/AC.

Automatic Identification System

The greatly stabilized air picture resulting from the addition of the AN/SPS-48 DDC and SGS/AC capabilities provided the opportunity to make possible further improvements within the battle group and exposed the need for additional battle group capabilities. The Automatic Identification (AutoID) System was one of those developments. The improved air picture fidelity showed obvious deficiencies in maintaining correct identification of the large air track population maintained throughout the battle group volume of radar coverage, often 100 to 300 high-fidelity automatic tracks.

With the exception of a few relatively primitive automatic aids to assist in identifying air tracks, the principal mechanism for air track identification was the operator evaluating the properties of each track and manually selecting the appropriate identification within each air defense system. Properties evaluated were typically identification, friend or foe (IFF) responses from aircraft, the location of air tracks in proximity to the battle group and other areas of tactical concern, and the kinematic behavior (course, speed, and altitude) of each track.

The resultant identification, sometimes called tactical identification, is based on probable intent. If a track headed toward a ship, with no apparent response or an unexpected response to IFF interrogation, that track would become one of significant command attention, and the resultant identification could be hostile, that is, it would appear that the intent of the track was hostile. The true identification of the track often could not be determined; there was simply too little information available to perform a "positive identification." Moreover, the fact that the track was flying along an airway, flying within the territorial waters of a country, or flying at high altitude or low altitude was not readily apparent unless the operator paid very close attention to the properties of that particular track. Even then, in the tension of the moment, mistakes were made in the interpretation of data associated with the track. In addition, the track population, which often exceeds 100 tracks that continuously are coming and going and most of which are commercial aircraft, introduce an overwhelming demand for operator attention.

The air defense problem within this so-called "violent peace" environment, where the vast majority of air tracks are commercial aircraft, could mean that only 1 out of 100,000 or more tracks evaluated over time intends harm to the battle group. That one aircraft, possibly emanating from the population of commercial aircraft, must be detected and deterred. On the other hand, the track population and the density of commercial aircraft in a declared hostile environment will be more sparse, and the operating environment would be much better controlled by the military. In this case, aircraft returning to the battle group could easily have experienced battle damage that may cause behavior to appear hostile, and the damaged aircraft could easily have lost radio communications capabilities. The disabled aircraft would likely be executing return-to-force procedures; however, in the heat of battle, the prescribed spatial and kinematical behavior of an aircraft executing these procedures may not be recognized by an operator who is also evaluating numerous other tracks under the intense pressure of combat. To further complicate the problem, allies are flying aircraft that were previously only flown by the enemy so that allied and enemy aircraft are often flying variants of the same type of aircraft.

Needed were computer processing capabilities to enable characterization of the operating environment and to automatically evaluate and revaluate the spatial, kinematic, and IFF data properties of each track. The product of this processing would faithfully emulate an alerted, relentlessly attentive radar operator making tactical track identifications throughout the volume of ship radar coverage. The capability would methodically and rapidly emulate the operator. Moreover, the capability would revisit each track periodically to validate decisions or change to an appropriate new identification. From these criteria the prototype AutoID System was developed.

Six fundamental identifications are shared among the battle group by TADIL exchange: friend, unknown assumed friend, hostile, unknown assumed enemy (or suspect), unknown evaluated, and unknown pending.

In defining required capabilities of the AutoID System, it was determined that the IFF capabilities needed control and processing improvements. These improvements included interrogation control, signal processing, and ship motion compensation. This improved functionality was necessary to implement high-confidence association of IFF to AN/SPS-48 DDC tracks, a fundamental ingredient to identifying tracks. In addition, there are situations where only the operator knows information pertaining to a given track; for example, the operator may be communicating by radio with the aircraft that constitutes the track under question. Therefore, the AutoID System had to be fully interactive with other elements of the ship air defense system to enable operator control of any or all track identifications.

To establish the operational environment within the AutoID System, it was designed to contain all countries of the world and the worldwide commercial airway database. In addition, the system contains a graphical user interface (GUI) that allows the operator to easily develop the rules for automatic track identification. The GUI enables the operator to easily establish rule-based ID doctrine that contains a hierarchy of ID statements and ID criteria. ID statements are organized hierarchically to enable physical ID statements to overlap. If a track fails to satisfy the ID criteria of the highest-ordered ID statement, the next underlying statement is evaluated, and so on, until all statements have been evaluated for various criteria established for each candidate track identification. Each ID statement can contain any number of ID criteria to establish the appropriate track identification. ID criteria can be established to apply to tracks throughout the volume of radar coverage or for discrete geographic areas such as a country or countries; operator-defined tactical areas; all, some, or one commercial airway; and return-to-force routes. ID criteria also contain provisions to stipulate speed, altitude, closest point of approach, and IFF response criteria for track identification. There are also GUI capabilities that support the entry of global rules to be applied to all ID statements and ID criteria.

To ensure that identifications are robust and stable, the AutoID System is designed to account for radar spatial and kinematic measurement errors. For example, if the speed criterion for a specific identification is to exceed 500 kt, track speed may need to exceed 520 kt to account for radar measurement errors and may need to drop below 480 kt to drop below the threshold, once that identification is made, to be declared below 500 kt. The exact criteria change with range and heading of the track to match the measurement characteristic of the radar. Similar spatial criteria apply around the boundaries of countries, airways, and operator-defined tactical areas. A criterion for declaring changes to IFF responses is also implemented within the system.

The prototype AutoID System was initially installed in the aircraft carrier USS *Forrestal* (CV 59). Figures 7a and 7b are images taken from the AutoID Control Console, depicting the results of a test scenario executed by the *Forrestal*'s Tactical Action Officer. The test scenario consisted of five aircraft closing on the ship. These aircraft were to behave in a manner that the automatic tactical identification, defined in the ID doctrine, was to be hostile. Also contained within the radar surveillance volume were aircraft that were to be identified as friend and other eligible identifications in addition to the hostiles; among these were commercial airline traffic.

Figure 7a shows the east coast of Florida, the Bahamas, and over-water airways within about 128 miles of the *Forrestal*, which was located in the center of the
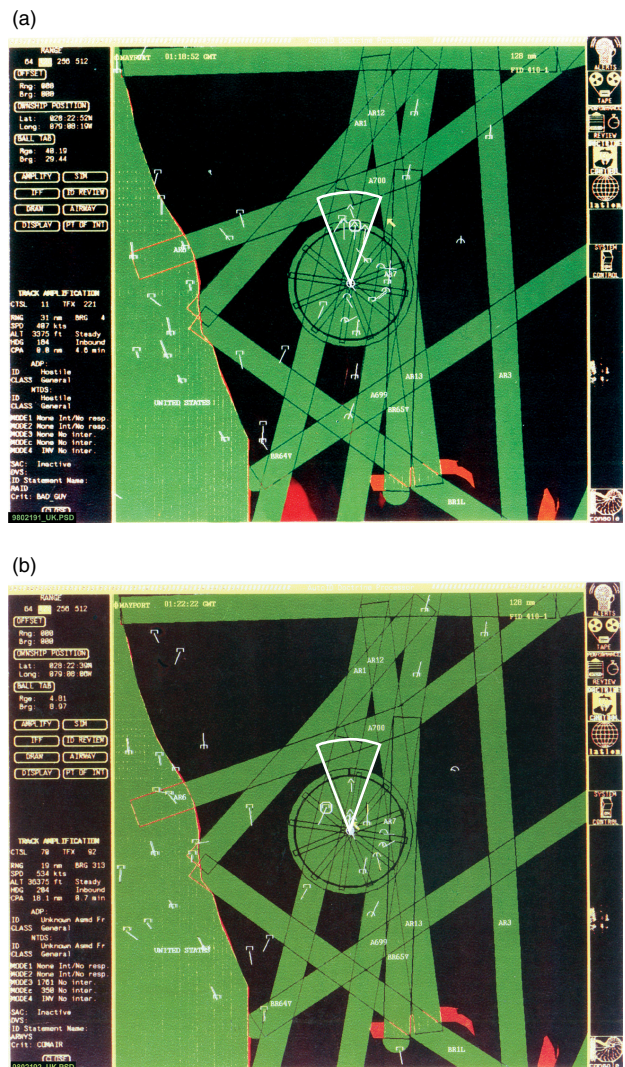

Figure 7. Automatic air track identification scenario; (b) was taken 3.5 min after (a).

display. Depicted about the *Forrestal* is a circle containing return-to-force airways. The wedge that extends from within the circle toward the top of the graphic (north) is a threat sector for this test.

Figure 7a was captured toward the end of the test. Shown within the threat wedge were five air tracks; four tracks were automatically identified as hostile (depicted as inverted Vs), and one track was identified as unknown (depicted as the upper half of a square). From the picture, it appears that the AutoID System correctly identified four of the threat aircraft and did not properly identify the fifth. However, from a subsequent picture taken about 3.5 min later (Fig. 7b), the entire scenario unfolded. In reality, mixed among the so-called hostile aircraft was a commercial airliner. The AutoID System correctly identified all aircraft, and the fifth hostile was late in attacking the *Forrestal*.

From Fig. 7a one can visualize where confusion would likely occur if a human were making instantaneous decisions in the heat of battle.

The AutoID System employed features such as IFF tracking and sophisticated use of ship IFF systems to achieve significant improvements in IFF performance, resulting in improved air defense system track continuity and the development of tactical identification at much greater ranges than ever before possible.

The AutoID System was successfully used during the *Forrestal* deployment to the Mediterranean Sea, to the Persian Gulf, and in the northern Atlantic Ocean. It was obvious that this system added another significant capability in the development of a battle group coherent air picture, prompting Navy leadership in battle management technology (at that time VADM Tuttle) to ask that an additional 10 AutoID Systems be built by the Laboratory to equip all aircraft carriers. Custody of these systems was transitioned to Navy in-service engineering activities to enable Fleet support of maintenance and operator training.

The AutoID System is the foundation for composite identification functionality contained within CEC, discussed later.

Multi-Frequency Link-11

Though the battle group was capable of mutual support through reliable automatic detection and tracking, gridlock, and automatic correlation of mutual Link-11 tracks, often the synergism experienced among air defense systems in the Laboratory and at land-based test sites was not present within the battle group. Obviously, something was drastically different within the operational environment. This discrepancy stimulated significant data collection and analysis activities to find the problem. After examining data from 20 different battle group operations, it was determined that Link-11 was reliably connected on average at a rate of only 61%. This poor connectivity caused the loss of great

amounts of data, resulting in the promotion of multiple tracks per aircraft and significant conflicts in data management.

Link-11 operations are normally conducted within the high-frequency (HF) radio band. At HF, radio energy frequently propagates over the horizon, and at the lower end of the HF band (frequently between 2 and 8 kHz) energy propagates on the surface wave effect that is gapless over the water to about 300 miles. The surface wave environment in theory will provide excellent connectivity among dispersed battle group ships operating on Link-11.

Numerous physics issues led to the Link-11 connectivity problem. First, HF propagation from the ship is distorted by the ship's superstructure, which often creates an antenna pattern similar to that shown in Fig. 8. These differ from ship to ship and frequency to frequency, often with ship noise sources also curtailing connectivity. Second, the HF operating environment is plagued with cumulative interference from a variety of effects, often received via ionospheric bounce (Sky Wave mode) from around the world, as shown in Fig. 9. To achieve adequate connectivity, the effects of these problems needed to be overcome.

The advent of a Link-11 Data Terminal Set (DTS) on a single circuit board enabled significant flexibility to implement improved methods of using Link-11 (previous DTS models were very large, many versions weighing more than 1000 lb). With the reduction in size and cost, multiple DTSs could be used, enabling the implementation of frequency diversity and improved signal processing techniques, thus the development of the Multi-Frequency Link (MFL) concept.
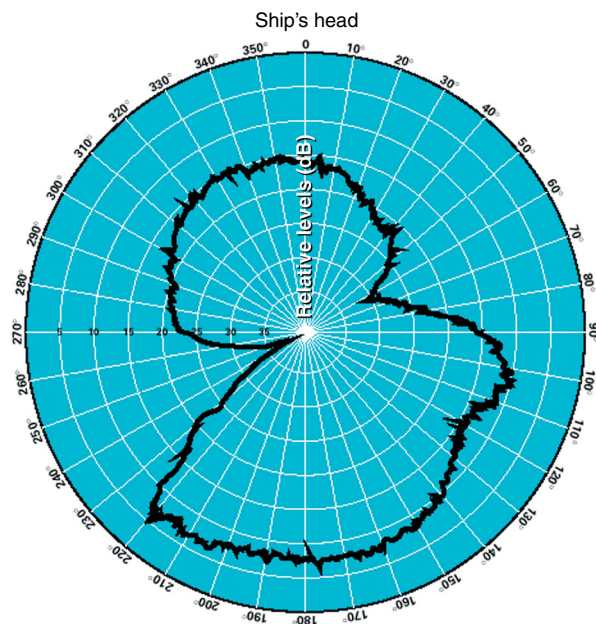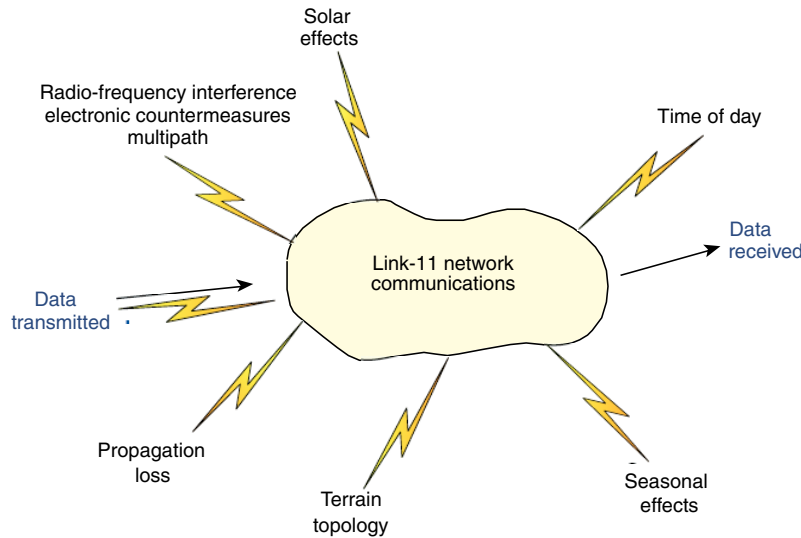

Figure 8. Typical ship HF antenna pattern.

Figure 9. Environmental impact on HF Link-11 connectivity.

The MFL controller enables synchronization of the four DTSs for data transmission and reception as well as selection of appropriate data received from each DTS. Each DTS and associated HF radio are typically operated in a dual-sideband mode. Upon receipt of Link-11 data, each DTS selects the sideband and combined sidebands with the best data quality and passes those data to the MFL controller. The MFL controller controls the combined reception of all DTS data frame by frame. Thus, for each Link-11 data frame, received every 13.3 ms, MFL sorts good data from bad data by evaluating a number of factors, including data parity. It then communicates the best of the received data to the local air defense system.

Based on the single-frequency results, the MFL was developed by using four DTSs, developed by Mikros Corp., a microprocessor-based MFL controller, and a display that enabled comprehensive operator control and information display. Three HF radios and one ultrahigh-frequency (UHF) radio are typically used to transmit and receive MFL data among units of the battle group (Fig. 10). Integration of these data across all frequencies on a frame-by-frame basis provided significant connectivity improvement.

As the result of employing frequency diversity (i.e., communicating over six HF sidebands—two per frequency—and one UHF sideband), Link-11 connectivity rose from an average of 61% to an average of 97%. Figure 11 depicts a running average of frequency contribution for a single ship over a similar 2-h period. The contributions of each MFL frequency varied significantly from ship to ship (which suggests the
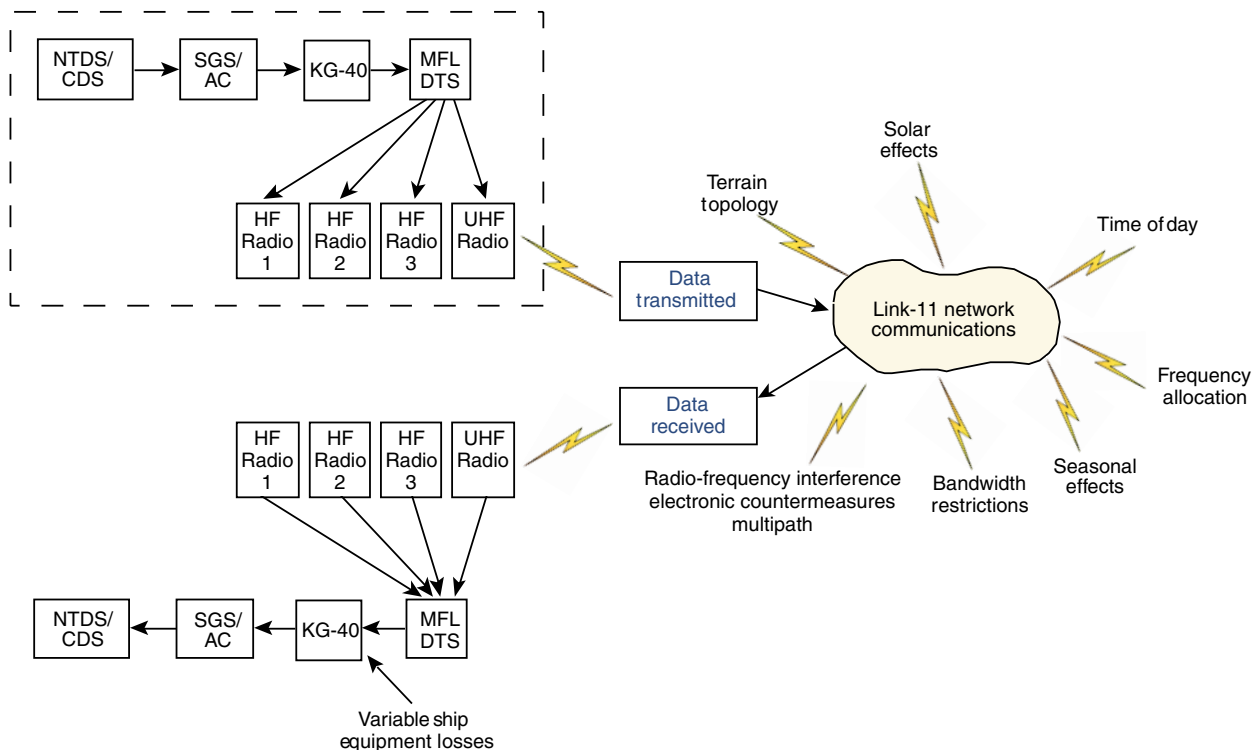
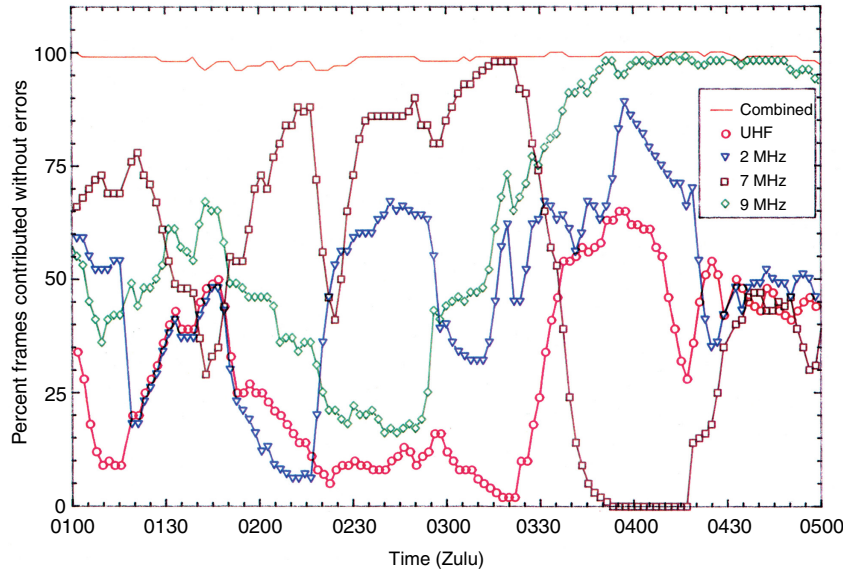Figure 10. MFL operations (CDS = Combat Direction System).

Figure 11. Contributions of individual frequencies to single-ship connectivity.

complexity of reliably propagating gapless surface wave HF Link-11), while accommodating the tactical requirement to vary the movement among combatants of a battle group.

MFL was initially deployed in four ships of the USS *Ranger* battle group: one aircraft carrier, two cruisers, and one destroyer. In support of the MFL capability, two extra HF radios were installed in each ship to augment radio capacity. The initial MFL capability was deployed for more than 8 months. During this period, typical MFL operations were verified to provide the improvement in Link-11 connectivity that was experienced during initial Fleet testing.

Significant improvement in Link-11 connectivity provided by MFL enabled rapid exchange of a moderate number of radar tracks (a few hundred) throughout the battle group. This improvement made possible continuous automatic gridlock and robust automatic track correlations (both provided by the standard SGS/AC installation, discussed previously) to support development of a mutually supported, reliable battle group track picture. With robust MFL data exchanges between battle group participants, data conflicts between units were also substantially reduced.

MFL capabilities were subsequently incorporated in the Common System Data Terminal Set produced by the Space and Naval Warfare Systems Command (SPAWAR).

FROM BGAAWC TO FACT

The need for the U.S. military services and allies to operate as a more unified force became most obvious during Operation Desert Storm. After Desert Storm in 1991, and signifying its commitment to Joint operations, Congress mandated that the Navy change the

BGAAWC program to the FACT program. From that time to the present, the FACT program has been developing capabilities with emphasis on the battle group as part of a unified force.

Dual-Net Multi-Frequency Link

As discussed previously, the MFL capability greatly improved battle group operations; however, when the USS *Ranger* battle group joined other battle groups, the Air Force, and allies to support Operations Desert Shield and Desert Storm, the force Link-11 network did not benefit from the four ships equipped with MFL. This was because most Link-11 network participants were not MFL-equipped. Moreover, those Link-11 participants not equipped with MFL were drastically reducing the effectiveness of the MFL network. Clearly, MFL needed to be made more adaptable to a mixture of MFL and single-frequency Link-11 capabilities. Dual-Net Multi-Frequency Link (DNMFL) was subsequently conceived. It was designed to fully connect the battle group with inherent MFL capabilities, to fully operate with single-frequency Link-11 network participants without diminishing the effectiveness of MFL and, where possible, to improve the overall performance of single-frequency Link-11 operations.

With the introduction of the Joint Tactical Information Distribution System (JTIDS), TADIL J (Link-16), additional TADIL capacity and capability were introduced to the force. By the nature of their respective capabilities and the infrastructure of systems installations, Link-11 and Link-16 will be operated together for many years to come. DNMFL needed to accommodate and foster the successful operation of both Link-16 and Link-11 capabilities.

DNMFL/J was designed to simultaneously support the operation of two or more Link-11 networks and the JTIDS Link-16 network. The typical DNMFL/J operational employment simultaneously supports a two or three HF MFL network, an independent asynchronous single-frequency Link-11 network, and the Link-16 network. DNMFL/J contains SGS/AC capabilities for each network to enable the capability of establishing a coherent gridlocked and correlated battle force track picture with multiple TADIL networks introduced with DNMFL/J and Link-16 (Fig. 12). DNMFL/J performs Link-11 communications functions and Link-11 track management functions, which include data forwarding
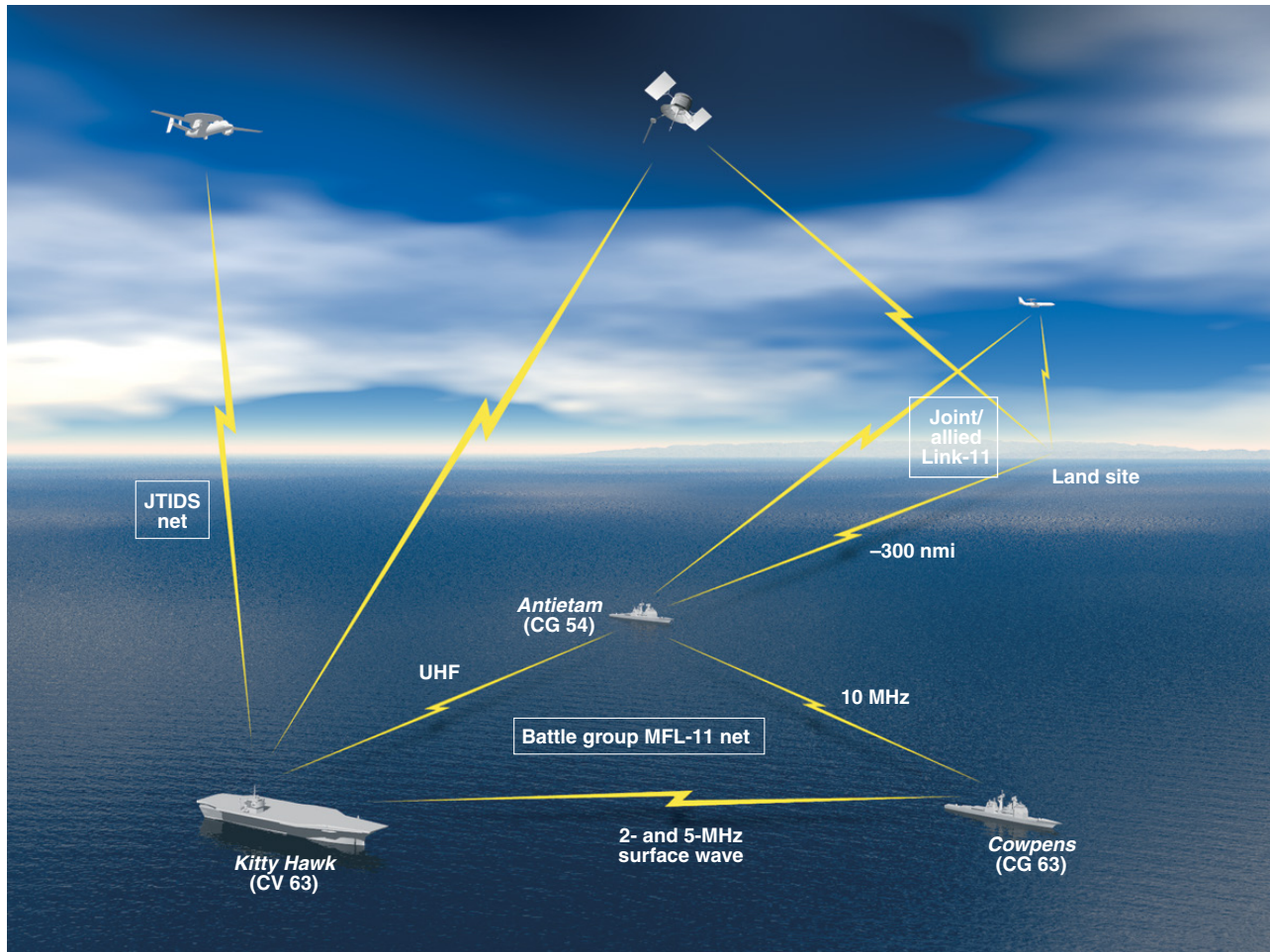
Figure 12. Typical DNMFL/J operations.

between multi-frequency and single-frequency Link-11 and the JTIDS networks; performs gridlock and track correlation activities for Link-11 and Link-16; and communicates Link-11 and Link-16 data seamlessly to the local air defense system. No modifications to air defense systems are required to operate with DNMFL/J.

Typically, units equipped with DNMFL/J operate on what is called the MFL Link-11 network. Those units equipped with single-frequency Link-11 operate on the single-frequency network. The multi-frequency Link-11 network typically operates at the fastest Link-11 network cycle time, the result of significantly better connectivity than the single-frequency network. Normally, the single-frequency Link-11 network would be connected at about 61%; however, DNMFL/J continuously evaluates which DNMFL/J-equipped participant is best connected to each single-frequency Link-11 network participant and communicates this reception quality among units of the multi-frequency network. From these single-frequency network connectivity evaluations, multi-frequency network DNMFL/J units automatically determine which multi-frequency network participant will forward data from each single-frequency

network participant to the multi-frequency network. This diversity operation takes advantage of multi-frequency network participant spatial separation and is performed on every network cycle of the multi-frequency network. The effect is to often improve single-frequency participant connectivity from the single-frequency network to the multi-frequency network—from an average of 61% to an average of 80% and more. The more DNMFL/J-equipped units distributed throughout the battlespace, the better the performance of this connectivity improvement feature.

When all principal air defense ships and the aircraft carrier are equipped with DNMFL/J, secondary networks can be added to provide more connectivity. Figure 13 depicts connectivity maintained during a USS *Kitty Hawk* battle group deployment to the Arabian Gulf.

Because of the lack of assets at times, the DNMFL/J multi-frequency network must operate with two, instead of three, HF radios. When this happens, the multi-frequency network connectivity typically averages between 90 and 93% rather than 97%. This reduced connectivity appears to degrade Link-11 performance minimally.
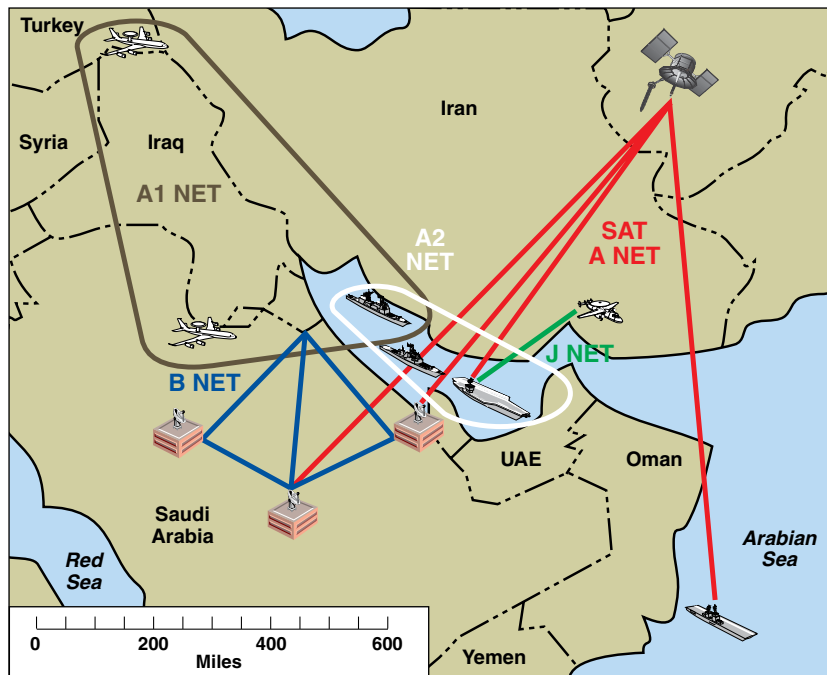
Figure 13. DNMFL/J operations in the Persian Gulf in the late 1990s.

The Laboratory-developed DNMFL/J prototype has been deployed within numerous battle groups. This capability is to be an integral part of the SPAWAR-developed prototype Multi-TADIL Processor (MTP). The MTP prototype will also leverage the capabilities of high-data-rate satellites in addition to DNMFL and JTIDS functionality.

Control and Engage Developments

Progress in the development of a mutually supportive battle group air picture provided the basis for developing mutually supportive control and engage capabilities to more effectively counter the air threat. Investigations to improve control and engage functionality led to the development of fundamentally new capabilities to counter advancements in the threat. These developments include capabilities to perform remote TADIL track engagements, weapons control, decision aids to assist in improving the efficiency of engagements, and advancements in articulation of the air picture.

Beyond the battle group, most recent control and engage advancements have been in the development of capabilities that plan the synergistic laydown of Joint services' air defense systems and support the synergistic execution of Joint theater air defense.

Remote Track Launch on Search

Remote track launch on search (RTLOS) was deployed during the Cold War in the 1980s when the enemy was expected to attack the battle group with large regiments of bombers equipped with long-range anti-ship cruise missiles. The RTLOS capability enabled designated ships, typically located well forward of the main battle group, to be less likely detected by the enemy by enabling control of radio-frequency emissions. This tactic increased the likelihood that the battle group could engage enemy bombers instead of their missiles, which is analogous to shooting the archer instead of the arrow(s). An example of an RTLOS scenario is depicted in Fig. 14.

RTLOS was practical largely owing to the capabilities of the previously described SGS/AC capability. SGS/AC compensates for both navigation and radar azimuth misalignments (gridlock) between the RTLOS reference ship and the missile-shooting ships. By limiting radar radiation to the time it takes to gridlock to the reference unit (Fig. 14), which is typically less than 1 min, the missile-shooting ship could remain in gridlock for a considerable period before needing to radiate radars to repeat the gridlocking process.

In practice, the RTLOS-shooting ship, equipped with the Terrier New Threat Upgrade (NTU) Weapon System, would fire its long-range Standard Missiles based on Link-11 (TADIL A) data received from a reliable tracking source, typically an Aegis cruiser. Mid-course commands to the missile, by the shooting ship, were based on Link-11 data received from the reference ship. The Terrier-equipped ship would radiate its fire control radar only during the terminal phase of missile homing, minimizing its exposure, and thus its presence, to the enemy. This was the very first type of cooperative engagement because the engagement was initiated with the data from a remote ship and completed with the data from the firing ship.

RTLOS was a tactic that was practiced in training and employed by all deployed battle groups during the latter stages of the Cold War.

Engage-on-Remote Data

Effects such as radar electronic countermeasures mandate the need for synergism and mutual support for the battle group to survive. The advent of CEC provided the wherewithal to support the complete engagement sequence, from missile launch to intercept, without the defending ship ever detecting the enemy. Engage-on-remote (EOR) was a concept developed within the BGAAWC program that was made possible because of the accurate composite tracking and rapid track updates provided by CEC. Figure 15 illustrates the EOR
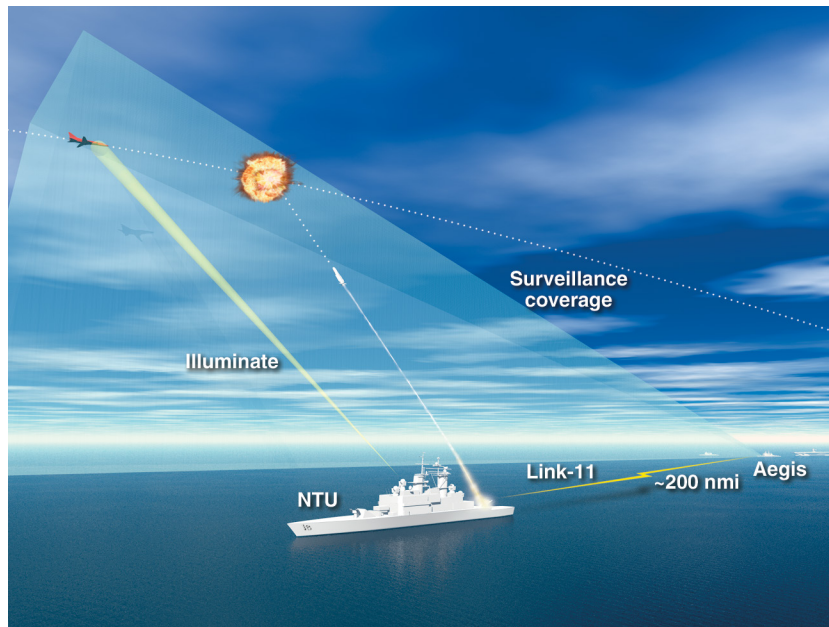
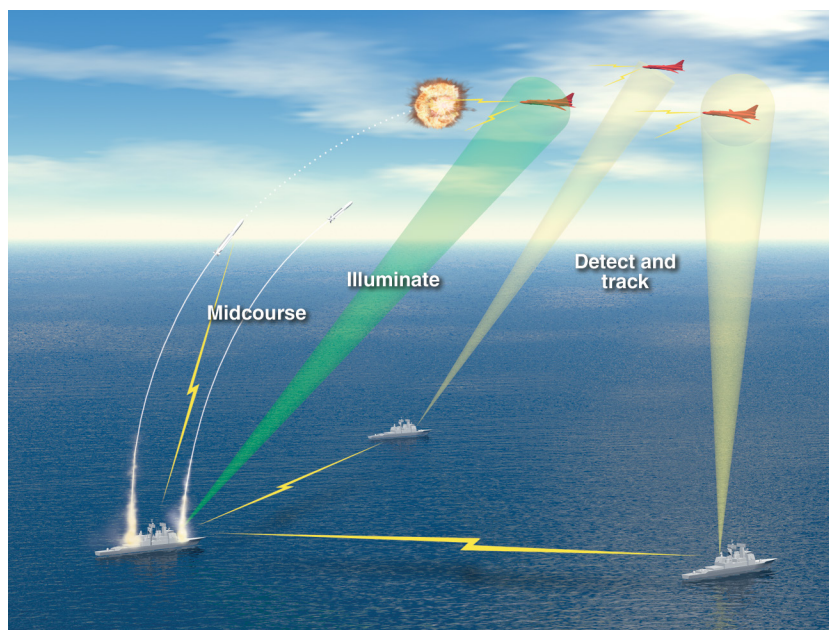**Figure 14.** Remote track launch on search.

Figure 15. Engage-on-remote.

concept. Synergistic battle group tracking provided by CEC makes this weapons control capability possible. All CEC-equipped battle groups have EOR capabilities among CEC-equipped Aegis ships. Additional discussion of EOR is provided in the articles by Duhon and by Grant in this issue.

Force Threat Evaluation and Weapons Assignment Capability

The Force Threat Evaluation and Weapons Assignment (FTEWA) capability was developed as a prototype

to improve display of the battle group air picture, provide decision makers with battle group–wide threat evaluation and optimized battle group weapons assignment decision aids, and station ships to optimize battle group air defense with the fewest assets.

Senior decision makers are often challenged by the need to decipher symbolic representations of the battle group air picture, as shown in Fig. 16. Moreover, to obtain supporting information associated with the displayed symbol, the decision maker must often become intimately familiar with the controls and complex data readouts associated with the typical command and decision console. When tensions are high and timely reaction is mandatory, rapid achievement of situational understanding can be the difference between life and death. Needed was the ability to perceive the battlespace in terms that are familiar to our visualization of day-to-day activities, analogous to the process depicted in Fig. 17, and the capability to transfer data into information. For example, senior decision makers during Fleet exercises have been able to immediately visualize the path of the suspect commercial aircraft climbing along the center of an international airway and to make the correct engagement decisions.

Improvements in establishing a battle group air picture, coupled with advancement in commercial graphics processing capabilities, made it possible to depict the battlespace in terms that can be intuitively understood by decision makers. Figure 18 shows the results of displaying the air picture in realistic terms on the FTEWA display. The FTEWA display showed military-friendly aircraft by recognizable type and commercial aircraft generically as well as aircraft relative altitudes and aircraft in level flight, climbing, and descending.

The display, by itself, provided decision makers with significant improvements in bringing about battlespace understanding; however, additional display functionality was needed. FTEWA introduced capabilities such as the Spaceball, a spherical trackball-type control that

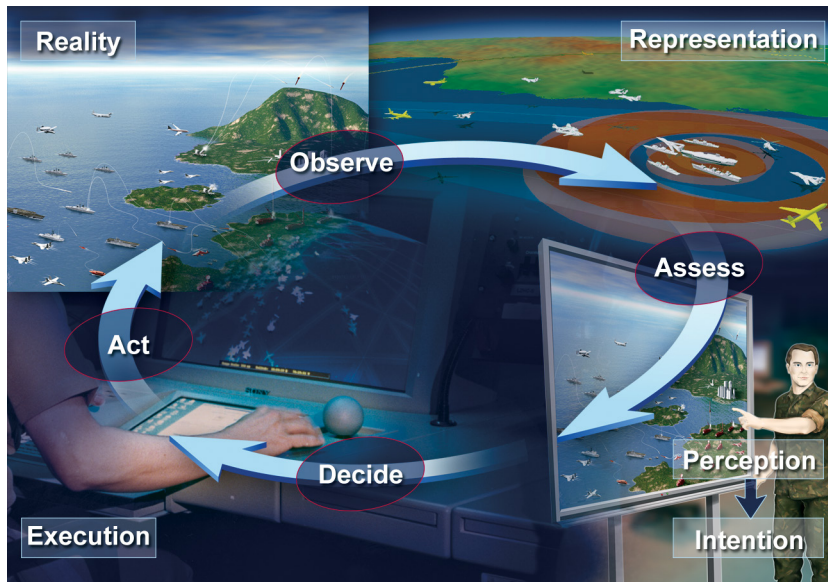**Figure 16.** Typical symbolic depiction of an air picture.

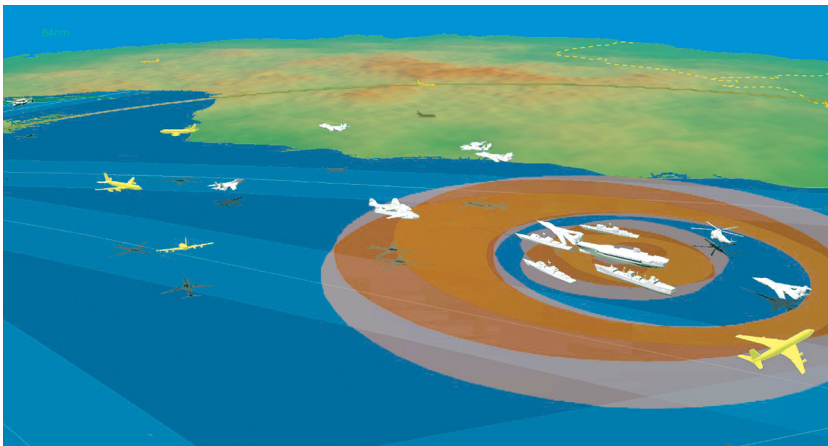**Figure 17.** Visualization of the battlespace.

Figure 18. FTEWA three-dimensional real-time display.

allowed the operator to manipulate the display in six degrees of freedom from a single control (animate the display range scale in and out, tilt the display elevation up and down, and rotate the display north orientation left and right). FTEWA also introduced voice recognition, allowing the user to command functionality that previously required numerous button actions and took attention away from the display.

The optimization of battle group air defense to counter the enemy over a large threat axis can be complex when assets are scarce. FTEWA provided the capability to plan the optimum stationing of air defense ships, resulting in mutually supported defense in depth.

In addition, FTEWA provided several aids to help decision makers evaluate the air threat and optimize the assignment of air defense weapons throughout the battle group. The threat evaluation capability evaluated and ranked the threat in relation to all friendly (TADIL) units, or selected units, within the battle group. The FTEWA probability of intercept leveling algorithm (known as pi-leveling) accounted for all force engagements and recommended an optimal shooter schedule based on the required probability of kill (amount of fire); earliest time to intercept; spatial and kinematic characteristics of weapons, shooter, and victim; and the current engagement loading of each missile-shooting ship.

FTEWA was the first real-time command support capability that was able to import the airspace control order and the air tasking order for use in airspace control and in associating friendly military aircraft displayed to the battle force air plan.

The battle group commander and his staff aboard USS *Kitty Hawk* (CV 63) initially evaluated the FTEWA capability. After successful operations during a 6-month deployment off the Korean peninsula, additional prototype systems were requested by the Navy and

deployed in USS *Cowpens* (CG 63) of the USS *Kitty Hawk* battle group, and aboard USS *America* (CV 66) and USS *Normandy* (CG 60) of the *America* battle group. FTEWA was also installed aboard USS *LaSalle* (AGF 3), the Sixth Fleet command ship. The FTEWA capability was the baseline that later evolved as part of the much more capable theater air defense Area Air Defense Commander (AADC) capability.

Area Air Defense Commander Capability

The AADC capability was developed to provide the Commander Joint Task Force (CJTF)

Figure 19. AADC planning process (COA = course of action).

with the tools to synergistically and efficiently employ Joint theater air defense systems at the operational level of war. At that level, the CJTF is responsible for the definition and defense of a theater-wide defended asset list (DAL), which could include cities, airports, seaports, and other assets vital for Joint theater operations. The AADC capability prototype was developed to enable the CJTF to rapidly assess risk and allocate scarce resources. This was accomplished by building a capability that supports continuous, dynamic, synchronized, collaborated, wargamed, and predictive theater air defense planning.

The reality of theater air defense operations is that circumstances may cause the CJTF to change the DAL or its priority order, change the friendly order of battle (available friendly weapons may be added, become battle losses, or be placed under another commander's operational control), change the enemy order of battle (enemy theater ballistic missiles and air-breathing threats that have been destroyed or moved), approve a new intelligence estimate, or satisfy component commanders who have requested additional force protection. These demands require a continuous dynamic planning process and cannot be accommodated by a single theater air defense plan.

The AADC capability provides the quality and response time necessary to build plans for theater defense that allow the AADC and CJTF to maximize protection of the DAL with the fewest air defense assets. It has altered the theater air defense course of action development process from one that consumes hours and days to one that can produce a plan in minutes (as illustrated in Fig. 19) with a small team of staff officers who are able to plan 24/7 (Fig. 20a).

In addition, the AADC capability contains current operations functionality that enables the AADC to visualize and audit the battlespace in real time, as shown in Fig. 20b. The AADC current operations
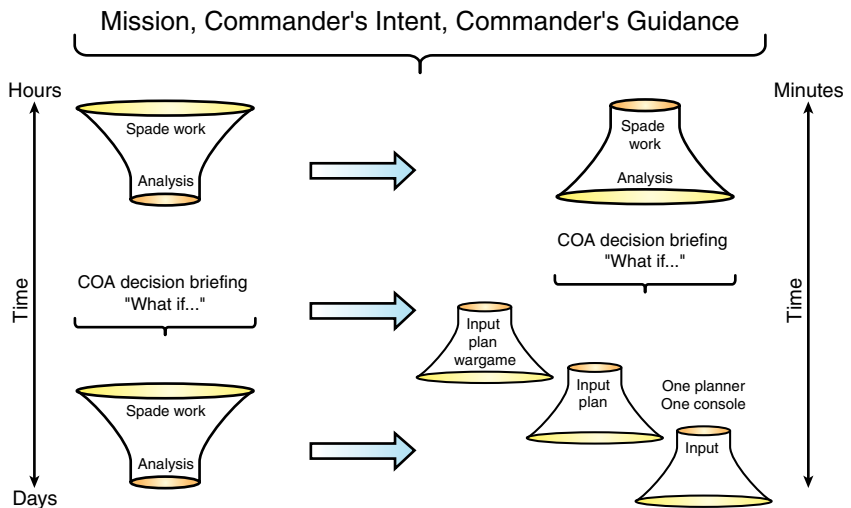
module receives TADIL information from the battle force, articulates the theater air picture in a realistic manner, and provides decision aids that assist decision makers in assessing the threat and assigning appropriate weapons as needed.

The AADC capability has been successfully demonstrated at APL and aboard ship in numerous exercises and wargames. Prototypes are deployed in USS *Mount Whitney* (LCC 20), USS *Shiloh* (CG 67), and USS *Blue Ridge* (LCC 19). Responsibility for system improvements and maintenance is transitioning, as designated by the Navy, to General Dynamics Corp. in Greensboro, North Carolina.

A more detailed discussion on the AADC capability is provided in the article by Prosser et al. in this issue.

BGAAWC/FACT AND CEC

CEC, an offshoot of the BGAAWC program, brings a revolutionary new capability to air defense by networking sensors and weapons from combat systems distributed throughout the battle force in a new and significantly more effective manner. This capability brings substantial improvements in track accuracy, continuity, and ID consistency; provides a nearly identical tactical picture to all CEC units; increases the battlespace; and reduces reaction time and extends engagement ranges through cooperative engagements. These characteristics are further discussed in articles by Grant, by Bath, and by Duhon in this issue. After reviewing the test data, Secretary of Defense Perry observed that CEC gives us a "15-year" head start on our adversary. A description of CEC is given in Ref. 3.

THE WEAPONS CONTROL LINK

As discussed earlier, the essence of net-centric warfare is the data links that "knit" the distributed sensors and weapons into a cohesive and synergistic air defense

Figure 20. AADC planning space (a) and current operations space (b).

SPS-type radars was also needed. (See the discussion on AN/SPS-48/DDC.)

- An automated mechanism for accurate gridlock alignment between radars on different ships would be required to ensure a "coherent" track picture. (See earlier discussions on gridlock and SGS/AC.)

- A highly capable weapons control link (WCL) with high availability and immunity to jamming comparable to the Aegis system was needed.

- Investigation of force AAW coordination algorithms was also needed in the context of a force network, based on studies by the APL Assessment Group that showed the potential value of coordinated fire to minimize damage and wasted engagements.

One result of the initial conceptual work was the decision to study the WCL concept further because it was concluded to be critical to such a weapon network concept and initial analysis had determined that present and developing tactical links could not provide the robustness and timing for weapons control. To meet the identified performance characteristics, the concept called for modern features (e.g., a spread spectrum and precision clocks), and initial analysis led to the conclusion that the system must be a directive point-to-point system with directive transmit and receive array antennas.

Although issues continued concerning whether such a high data capacity (hundreds of kilobits per second to megabits per second) link was needed for the entire task force engaging a surge attack of Soviet cruise missiles or whether a lower data rate could suffice, the need for high availability in propagation fading environments as well as intensive electronic countermeasures was clear. The WCL had to be as robust as the Aegis and Standard Missile elements it supported. Because it was concluded that no existing data links or none under development could support the conceptual requirements, a study was launched to determine WCL requirements on power and gain to achieve the upper-bound data rates. The requirements were recognized to be quite dependent on frequency band because the effects of natural phenomena as well as projected enemy jamming technology were frequency-band

system. Recognizing this, the Aegis Defense System Acquisition Review Council in the early 1970s directed the Aegis program manager to find a way for Aegis ships to benefit the entire Fleet. A key concept born at APL in response was the Force Weapon Control System (FWCS). The FWCS concept called for a networking of fire control components of a task force (i.e., carrier battle group of the time) consisting of Aegis and Terrier/Tartar air defense ships. The network was envisioned to allow common use of data for coordinated and, later, cooperative engagements. Studies performed during 1973–1975 included gridlock sensor alignment, link data rates, link characteristics for high anti-jam margin, and computing power for a centralized architecture (with Aegis as the central node with the requisite processing power). From these studies a number of insights were gained:

- Automatic detection and tracking equipment with target false alarm control would be needed for all contributing radars. Although the SYS program was under way, an interim capability for the

dependent. Therefore, a parametric analysis was commenced to evaluate potential design characteristics versus frequency band.

Initially, a ship-to-ship connectivity was analyzed for a frequency range from about 100 MHz through 30 GHz (essentially the very high frequency [VHF] and microwave bands). This analysis was extended to 100 GHz (into the millimeter wavelength band). Next, because it was determined that horizon limitations as well as the potential desire to connect to airborne surveillance could require similar availability of surface-to-air links, a surface-to-air study was also performed over the 100-MHz to 100-GHz frequency range. Because there was interest in determining the potential of upgrading lower-frequency communications for such a purpose, the study was extended down to 1 MHz into the HF band. The study took into account the emerging concepts of operations of the not-yet-deployed Aegis system and the need for coordinated capability against low-flying cruise missiles.

Figure 21 illustrates the various propagation and interference effects that had to be input or varied during this analysis. In the 1- to 30-MHz HF band, the key factors are ground wave and sky wave propagation, atmospheric interference propagated over very long ranges via these modes, and limited coherent bandwidth. Above about 100 MHz (VHF) is a transition from the ground/sky wave regime to the free space propagation regime in the UHF and microwave bands. This is characterized by reflective interference known as multipath, the Earth horizon shadow, refractive lensing from atmospheric density variations, and attenuation from rain and atmospheric gases.

The resulting body of study data during the 1970s comprised a nine-volume Data Linking Series. A tenth volume was written to consolidate the findings and provide the technical basis for what became the requirements for the CEC Data Distribution System.

Figure 21 also illustrates the summary results of the data link studies. The following was concluded:

- Above about 10 GHz, link signal loss in rain scattering and atmospheric gas absorption was beyond the technical capability for the extreme link availabilities required (comparable to that of telecommunications).
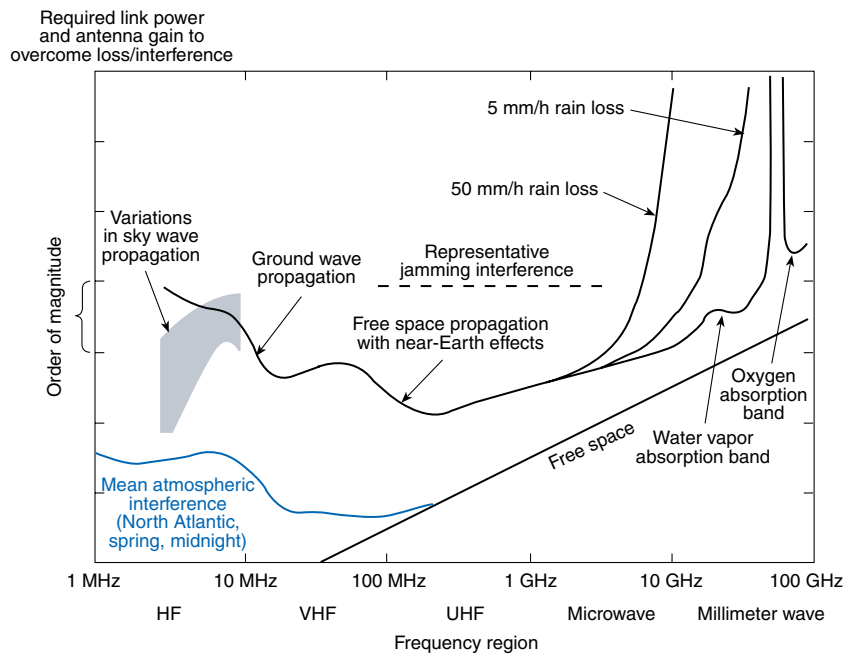
Figure 21. The required link product of power, transmit gain, and receive gain is shown versus frequency from 1 MHz through 100 GHz for a normal 20-nmi ship-to-ship range, i.e., within line of sight. The sky wave case shows the potential variations in required power/gain product for nighttime communications beyond the horizon, depending on ionospheric conditions. The product is scalable depending on required information bandwidth, with high bandwidth requiring more power/gain.

- Below about 1 GHz, practical link antenna gains (for apertures sufficiently small for ship and aircraft installation) and limitations in available antijam margin spread spectrum bandwidth could not meet the jamming resistance and upper-bound data rate requirements.
- A full measure of spread spectrum and both transmit and receive antenna gain as well as high-power transmitters would be required in the best band, the microwave band, to achieve the high data rates, propagation fade margins for high availability, and requisite jamming resistance comparable to Aegis.
- Available frequency allocations favored the mid-microwave band.
- Even with the high power and gains and spread spectrum, a practical WCL would still not be able to meet the requirements without also featuring path diversity gain, a practice of the telecommunications industry of providing simultaneous alternative paths to a destination should one path be faded or interfered with.
- Expected timing stringencies would likely require use of a phased array, transmit/receive antenna for each link terminal.

The study results indicated the need for requirements about 3 orders of magnitude more stringent than any
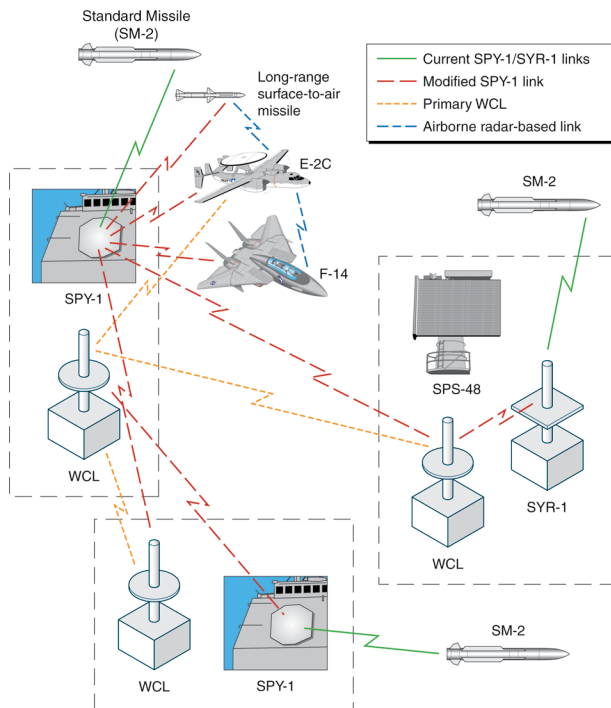
Figure 22. WCL force concept.

existing or planned tactical link under development at the time (and even today). This was the first time that the need for additional power/gain margin against propagation fading and path diversity design was required of a tactical Navy (nonsatellite) link.

In the early 1980s, as part of the BGAAWC program, APL began to develop a prototype of key attributes of the WCL. An early concept of WCL involving multiple links is shown in Fig. 22. Initially, it was decided that extension of the two Navy weapons links already involved in air defense, Aegis SPY-1 missile link and Terrier SYR-1 missile link, be considered in the development of design concepts. A study of an adjunct transmitter using SPY technology was examined, but it was determined that the required WCL duty factor (transmitter "on" time) would jam the SPY-1 radar if in the same band. Thus, operating WCL in the SPY frequency band would not be practical.

The other weapons link considered was the phased array system for control of the Terrier/Tartar Standard Missile midcourse guidance known as SYR-1. This array link operated slightly below the SPY-1 band and was a practical frequency band and waveform approach for WCL. It was later concluded in interactions with the frequency allocation advisors in the Navy that the SYR-1 band would be too crowded with other systems. It was, at the time, informally concluded that the mid-microwave band 4- to 7-GHz region was available and offered sufficient spread spectrum bandwidth, as well as having the potential of meeting all the performance

criteria as described in Volume 10 of the Data Linking Series. Concurrently, APL, in conjunction with RCA (now Lockheed Martin), began exploring engagement coordination and cooperative engagement concepts. As a result, Aegis-to-Aegis missile engagement coordination and remote magazine launch concepts as well as required performance parameters were developed. Force coordination concepts were later implemented into CEC. The remote magazine launch concept has been proposed from time to time, most recently for the Arsenal Ship.

During the same period, under APL subcontract, ECI began investigating converting the wideband SYR-1 concept (originally known as the special-purpose link demonstration concept) to a mid-band microwave configuration featuring the transmit/receive array and diversity characteristics. At about this time, through reviews of this concept within the Navy, the original concept was renamed Cooperative Engagement, and the WCL became known as the Data Distribution System.

THE FUTURE

The BGAAWC and FACT technology developments discussed above led to many of the current key Navy and Joint services battle force capabilities and have provided an approach to the future:

- A better understanding of air defense problems from first-hand experience
- Innovations toward problem solutions
- New large-scale, ground-breaking concepts as part of a force technology road map that could be studied and explored, even if considered "far out"
- A continuing multidisciplinary systems engineering approach to the force

Also described in this article are the early visions of the future that were set in place and have undergone implementation through the present. But what of the more distant future? Where could and should battle force engineering take us in the next 20 years? Where are the seeds of the CEC and automatic correlation ideas that led to implementations of the 1980s and 1990s? "The Road Ahead," the concluding section by Constantine in this issue of the ADSD series of the *APL Technical Digest*, explores these questions further. Even now, new types of ships (e.g., DDX and CVX) are on the drawing boards and naval involvement in long-range ballistic missile defense is growing. So, we see the need for major increases in all air defense battle force capability and integration areas.

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