

## SSDS Mk 2 Combat System Integration

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**T**he development of the Ship Self-Defense System (SSDS) Mk 2 required integration with shipboard equipment such as the Rolling Airframe Missile weapon system, the NATO Seasparrow Surface Missile System (NSSMS), and various sensors and other specialized ship systems, as well as integration with the Cooperative Engagement Capability (CEC). Essential to success was the decomposition and flowdown of self-defense requirements across the integrated combat system elements, and the introduction of critical technology advancements. Major advancements are provided by the SSDS implementation of a tracking filter customized for weapon support, tight coupling of CEC with SSDS through a high-fidelity interface, and introduction of NSSMS fire control radar measurements.

### INTRODUCTION

The Ship Self-Defense System (SSDS) Mk 2 integrates sensors and weapons to provide automated detect-to-engage capability. The process that led to integration started with a decomposition of combat system requirements and allocation of those requirements to SSDS and other elements. SSDS Mk 2 is designed for CVN ship classes that have the Cooperative Engagement Capability (CEC). A primary role of CEC is inter- and intra-platform netting of long-range surveillance sensors (e.g., AN/SPY-(), AN/SPS-49, and AN/SPS-48 radars). On these ships, remote AN/SPY-() radars and ownship surveillance radars have a pivotal role in self-defense. Because CEC integrates these radars, it was necessary to allocate SSDS Mk 2 requirements associated with them to the CEC/SSDS adaptive layer which is designed

as a tailored module for each new combat system application. CEC provides composite tracks, sensor measurements associated with each track (Associated Measurement Reports or AMRs) of interest, and statistics for false tracks/engagement control. SSDS filters the AMRs for engagement applications and prevents false engagements using CEC-provided statistics. SSDS requests certain short-term services from CEC such as identification, friend or foe (IFF) interrogations; AN/SPQ-9B lookback; and AN/SPS-49 high diver coverage. The interface between SSDS and CEC is a high-fidelity interface that transfers composite track, identification (ID), engagement, sensor measurement, and control data between CEC and SSDS. SSDS integration with the NATO Seasparrow Missile System

(NSSMS) is a major advancement that supports both Rolling Airframe Missile (RAM) and NSSMS engagements, improved CEC track continuity, and improved resistance to degradation. This article also describes how gridlock and alignment functions in CEC were integrated with SSDS.

## REQUIREMENTS AND THEIR ALLOCATION

The requirements flowdown and allocation process is illustrated in Fig. 1. Among the top-level requirements, the Operational Requirements Documents (ORDs) are typically written for acquisition of specific systems. The Anti-Air Warfare (AAW) Capstone document levies the probability of raid annihilation self-defense requirements on different surface ship classes. Combat system performance objectives and thresholds are initially specified in the Cornerstone Requirements document, and a Concept of Operations (CONOPS) document spells out how Navy operators will use the combat system. These high-level requirements are the basis for the more detailed combat system performance and compatibility requirements (P&CR). The P&CR includes allocation of requirements among the combat system elements, a critical driver in developing the requirement specifications for those constituent systems. Table 1 gives the functional allocation for the CVN class.

## IMPLEMENTATION OF SSDS Mk 2 REQUIREMENTS ALLOCATED TO CEC

### CEC Adaptive Layer Approach

Important technological advancements were implemented in CEC for integration with SSDS Mk 2 by tailoring the CEC adaptive layer. For all combat system applications, CEC code is partitioned into a kernel and an adaptive layer. CEC core functions such as composite track management and gridlock, necessary for inter-platform netting of surveillance sensor data, are implemented in the kernel and are common to all units in a battle force. The adaptive layer code is tailored to meet the requirements of each combat system application and to interface with the combat system elements unique to that application. This approach allows CEC to meet the requirements of each combat system application without affecting the implementation of other applications. The requirements allocated to CEC for the SSDS Mk 2 combat system application were implemented in the CEC adaptive layer.

### Self-Defense Track Disclosure and False Track Control

CEC is required to provide rapid self-defense track disclosure and to support control of false engagements by SSDS. For effective ship self-defense, threatening tracks

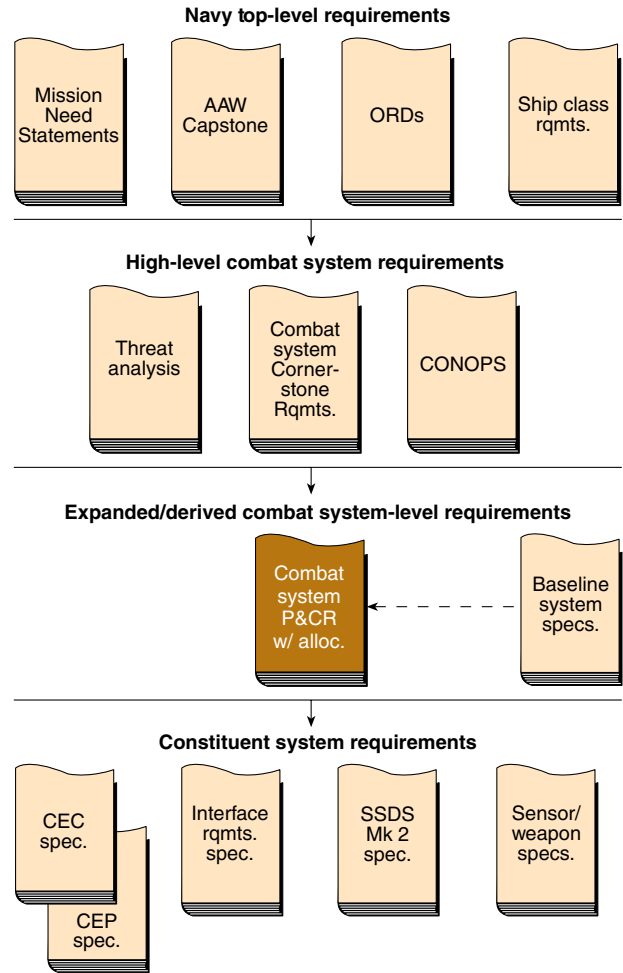


Figure 1. Combat system requirements flowdown and allocation.

must be disclosed at the earliest possible moment. Automation of self-defense engagements, however, requires the mean time between false engagements to be many, many years. Since engagements are initiated on the basis of tracks near the ship that exhibit threatening posture, the mean time between apparently threatening false tracks must also be many, many years. To meet the rapid disclosure requirement, an SSDS Mk 1 algorithm that exploits highly accurate Doppler range rate estimates was adapted for CEC. To meet the false engagement requirement, SSDS maintains a system track quality to monitor each track's potential for false engagement. The environmental monitoring function used by CEC for false track control produces activity estimates that SSDS uses to control false engagements. These estimates are mean time between false tracks (MTBFT) and probability of false association  $P_{fa}$ .

Self-defense requires that threatening tracks be disclosed rapidly but with a well-controlled rate of false track disclosures. The CEC local sensor tracking functions employ environmental activity estimation and adaptive length promotion to disclose tracks as fast as permitted by the environment, consistent with the

**Table 1. Functional requirements allocation for the CVN combat system.**

Combat system requirement	SSDS Mk 2	CEC	SPS-49A	SPS-48E	SPQ-9B	UPX-29	SPS-67	SLQ-32	TADILs	RAM	NSSMS
Target detection			X	X	X	X	X	X			From handoff or available search modes
RF emitter detection/class.								X			
Sensor interfaces	[4] NSSMS Mk 9 TIs, SPS-67, SLQ-32	SPS-49A, SPS-48E, SPQ-9B, UPX-29									
Local sensor tracking	SPS-67, SLQ-32	SPS-49A, SPS-48E, UPX-29			X			X			Local track
Contact association w/ composite tracks	Mk 9 TIs, SPS-67	SPS-49A, SPS-48E, UPX-29			X						
Composite track management/filtering		X									
Custom filtering for weapons	X										
Radar-emitter association	X										
Track identification	System ID	Composite ID									
Track distribution in force	Interface to TADILs	Composite tracks							System tracks		
IFF demand interrogation	Decision/request	Initiate				Execute					
Surveillance upspot	Decision/request	Radar control and elevation estimation	Antenna upspot response								
Sensor cueing	Decision, HDR request, TI designation	HDR request to SPQ-9B			Execute HDR						Acquire designated tracks
Track promotion and quality calculation	System track quality	Initial MTBFT and $P_{fa}$									Provides $P_{fa}$
Threat evaluation	X										
Engagement decision	Via doctrine										
Weapons scheduling	X									Status	Status
Weapon designation	X										TIs acquire track
Weapon firing											
Air control	X							EA	X	X	X
Operator support (consoles)	26										

HDR = high data rate; IFF = identification, friend or foe; MTBFT = mean time between false tracks; NSSMS = NATO Seasparrow Surface Missile System; RAM = Rolling Airframe Missile; TADIL = tactical digital information link; TI = tracker/illuminator;  $P_{fa}$  = probability of false association.

surveillance false track goal. Adaptive promotion leads to long disclosure times in dense environments. An alternative solution is needed for self-defense.

The AN/SPS-49A and AN/SPS-48E radars have been modified to produce high-confidence Doppler measurements with low probability of false detection. An SSDS Mk 1 algorithm exploiting highly accurate Doppler range rate estimates from the AN/SPS-49A radar was adapted for CEC. The self-defense algorithm discloses a track using one to three contacts. Single-contact disclosures use Special Alert contacts from the AN/SPS-49A radar. Special Alert contacts have a high inbound range rate and a short time-to-go (to ownship). This is the primary path for disclosure of stressing threats by the AN/SPS-49A radar. It has been successfully demonstrated and deployed in SSDS Mk 1 on at least 12 LSD 41 class ships.

Two- and three-contact track disclosures, using Doppler measurements from both AN/SPS-48E and AN/SPS-49A radars, are available within designated self-defense sectors for non-Special Alert detections. Figure 2 shows false track expectation curves for a representative surveillance sensor. The  $M/N = 4/7$  and  $3/5$  curves correspond to promotion rules that require  $M$  contacts to fall within appropriately sized spatial association windows in  $N$  observation opportunities. Four contacts in seven opportunities represent nominal track disclosure for many surveillance tracking systems. An acceptable false track rate near the center of the logarithmic scale corresponds to a density of environmental contacts that fall randomly within the association windows to produce that number of false tracks. If the input contact density increases, the tracker must use longer promotion or throw away input contacts to maintain the acceptable false track rate. The faster three-out-of-five disclosure path could attain the same false track rate only in a benign environment.

Contrasted with these disclosures is a short, Doppler-assisted promotion characteristic for a similar sensor

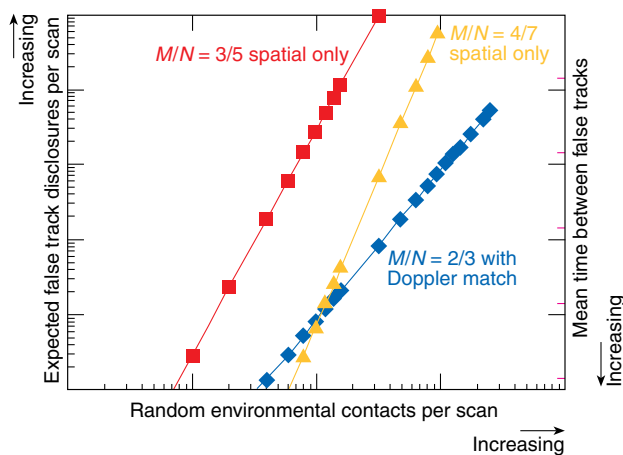


Figure 2. Self-defense false track rates.

that produces accurate Doppler rate estimates for real targets with high probability. The process requires the difference of the range rate estimates from the two initiating contacts to fall within a rate match window. The accuracy of the Doppler estimates supports a very narrow window, providing a significant reduction in false tracks relative to the spatial-only association processes. At the nominal false track rate, Doppler-assisted promotion permits track disclosure with only two contacts at an input contact density greater than that supported by  $4/7$  spatial association. Alternatively, relative to  $3/5$  spatial association, track disclosure based on two contacts can occur at the same contact density but at a significantly decreased rate of false track disclosures.

The reduction for the AN/SPS-49A is even better than this because the radar does not produce false Doppler estimates at a rate comparable to non-Doppler environmental detections. This permits Doppler association to operate at a much-reduced effective density of environmental input contacts. The false track rate slides down the curves to the left so that the rate of false “quick reaction” track disclosures is several orders of magnitude less than the spatial association rate. Thus, quick reaction disclosure paths that support the self-defense requirements were added to the surveillance tracker with negligible impact on system false track rates.

Conventional area defense tracking systems are designed to limit distracting false track disclosures to system operators, maintain operator confidence, and for CEC, prevent excessive false track propagation from networked sensors. Automated ship self-defense places more stringent requirements on the rate of false track engagement than can be met by the tracking system, even with Doppler-assisted track disclosure. Meeting these requirements necessitates contributions to false track control at each stage of processing; the sensor does its part, the tracking system does its part, and the control and engagement systems achieve the final reductions required for automatic engagement of imminent threats. Fortunately, the fundamental features already designed into CEC for false track control produce activity estimates that SSDS can use to control false engagements. The CEC local sensor tracking function provides estimates of MTBFT with each track disclosure and probability of false association  $P_{fa}$  with each update. SSDS uses these to maintain a track quality from which it determines when it can proceed with an automated engagement.

The tracking system’s environmental activity monitor estimates the rate of false track disclosures per sensor scan in a Poisson-distributed environment at the contact density surrounding each input contact. This permits the assignment of a promotion rate for a track incorporating the contact. The tracking system computes the false track estimate for each initiating and updating contact up to track disclosure. At disclosure,

the tracking system provides the MTBFT estimate based on the largest false track estimate for all contacts contributing to the track. The MTBFT is the logarithm of the reciprocal of the false track expectation expressed in false tracks per hour:

$$MTBFT = \log_{10} \left( \frac{1}{E[N_{FD}](f \text{ t/hr})} \right). \quad (1)$$

The  $P_{fa}$  estimate uses the contact density from the environmental activity monitor and the size of the association window for the track-to-contact association, based on the variance of sensor measurement and track prediction.  $P_{fa}$  is computed as

$$P_{fa} = 1 - \left( 1 - \frac{A}{G} \right)^{N_C}, \quad (2)$$

where  $A$  is the size of the association window in sensor measurement coordinates,  $G$  is the size of the self-defense region, and  $N_C$  is the number of input contacts per scan in region  $G$ .

SSDS initiates the system track quality based on MTBFT at track disclosure, engaging the track if it meets automatic self-defense criteria and has sufficient quality. If the system quality does not support the required probability of false engagement, SSDS iterates the quality for each updating contact, based on the contact's  $P_{fa}$ . The  $P_{fa}$  iteration updates the quality to the level corresponding to the MTBFT that would have been reported by the tracking system if it had withheld track disclosure until the updating contact.

### AN/SPS-49A High Diver Coverage Capability

CEC is required to support SSDS coverage requirements for self-defense. In CVN class ships, the primary sensor for high-altitude surveillance is the three-dimensional AN/SPS-48E. However, the AN/SPS-48E coverage is degraded by the ship's mast over part of the surveillance volume, and it can be degraded by electronic countermeasures or a casualty condition. To overcome these drawbacks, CEC implemented a 49 Upspot Mode, in which the two-dimensional AN/SPS-49A antenna beampointing angle is automatically controlled to provide high-altitude coverage and estimation of target elevation. The upspot mode provides an elevation estimate from the received target signal as the antenna upspot angle varies. This capability is deployed operationally in SSDS Mk 1, where it enabled the AN/SPS-49A to track and estimate the elevation of supersonic targets with sufficient accuracy to engage them with RAM.<sup>1</sup> In the SSDS Mk 2, automated radar control and elevation estimation processing were allocated to CEC, and automated processing to request upspot was allocated to SSDS. CEC provides No Upspot, Low Upspot, and High Upspot modes. In Low Upspot (the preferred mode) the antenna beam is kept on the horizon until SSDS requests upspot on a target, by making it upspot eligible. CEC will automatically upspot the radar antenna if the eligible target signal indicates a high diver. Thus, in Low Upspot mode, the radar power is maintained on the horizon until a potential high diver is detected. Figure 3 shows a block diagram of the elevation estimation algorithm.

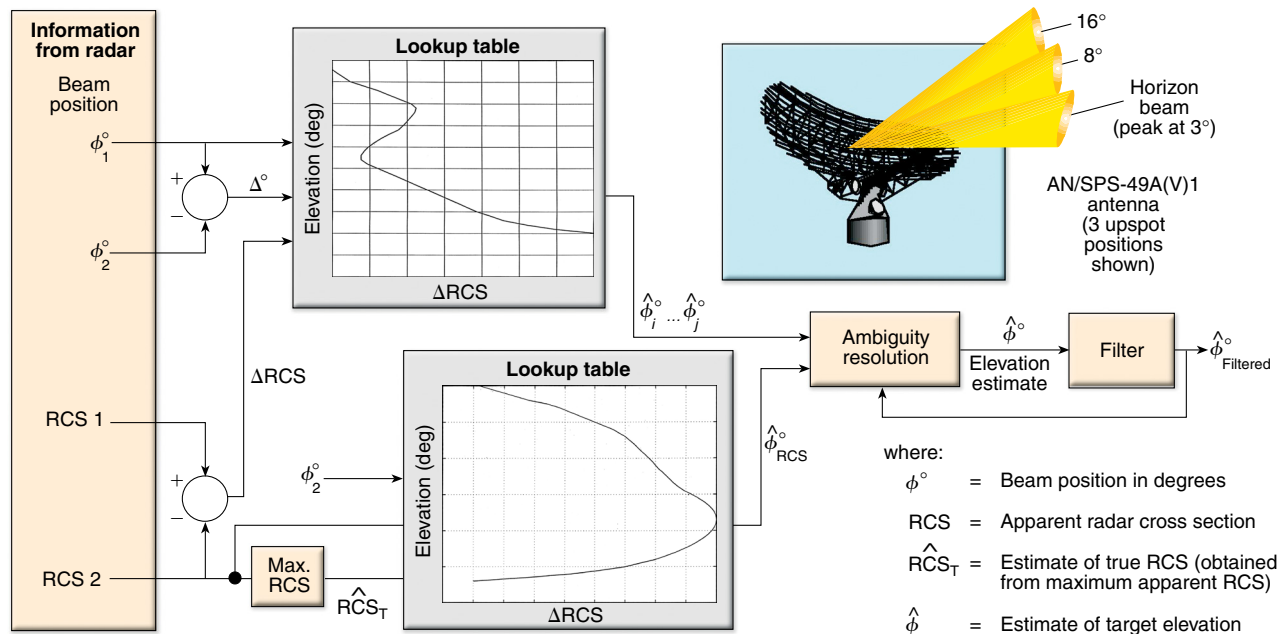


Figure 3. Basic elevation estimation.

## Incorporation of NSSMS Mk 9 Fire Control Radar Measurements

CEC is required to maintain track continuity on SSDS threats, including targets that execute stressing maneuvers. The AN/SPS-48 and -49 radars alone do not provide the update rate necessary for CEC track continuity on certain maneuvering threats. By integrating track data from the NSSMS Mk 9 radars, CEC can maintain track on these threats so that it can continue to provide critical range information to SSDS, which is not available from the Mk 9 radar. Adaptive layer functionality was implemented in CEC to accept updates from the NSSMS Mk 9 radar. The sensor invariance feature of CEC allowed selection of filtering parameters to accommodate the high update rate and accurate Doppler measurements. Additional modifications were made to essentially ignore the potentially biased Mk 9 range measurement.

## SSDS FEATURES FOR INTEGRATION WITH CEC

### Custom Filter

To properly motivate the SSDS custom filter, it is necessary to examine the premise and purpose of filtering: a filter is a process for estimating the state of a system from noisy measurements of the system. In this case, the system in question is a target, and the quantities of interest are its kinematics. The objective is to capture the target's motion while reducing the random variation of the measurements. To do so, a filter provides not only the estimate of the target's position and velocity (or, equivalently, its range and angles with their respective rates), but also a model for the error of this estimate. These products reflect the two principal functions of a filter in a multisensor, multitarget environment: (1) association (deciding which set of measurements originated from a particular target and should therefore be grouped for filtering the target track) and (2) estimation (combining the grouped or associated measurements using stochastic models of both the sensors and the target to provide an estimate of each target's motion).

The Kalman filter and its variants provide the most popular filtering framework. In addition to its computational efficiency, the Kalman filter's chief selling point is

its optimality: if the models for the target motion and measurement noise variance are accurate, the filter is the minimum variance linear filter. Furthermore, if the additive target process noise and measurement noise are Gaussian (as is commonly assumed), the filter produces the most likely estimate of the target state given the grouped measurement sequence.

Unfortunately, the models that represent target motion and measurement processes do not precisely represent reality; rather, the faithfulness of their representation is traded against the complexity of implementation to reach a "sweet spot" where the modeling fidelity provides estimates sufficient for the application without exceeding the computational resources of the system. In addition, the notion of modeling fidelity can be applied to the defensive weapons that the filter serves. The three constituents—targets, sensors, and clients—are bound together by the performance characteristics desired for the filter. For example, the filter used to schedule engagements is made deliberately sluggish so that the assignment of weapons to targets does not fluctuate wildly. The filter for pointing the NSSMS Mk 9 tracker/illuminator (TI), conversely, is much more responsive so that the target is painted with sufficient radio-frequency (RF) energy to support acquisition and terminal homing by the missile. This triad, together with the optimality criteria binding them, is depicted notionally in Fig. 4. Each type of model has elements that, taken together with the desired filter characteristics, can legislate a very different filter design according to how they are prioritized. Figure 5, the configuration

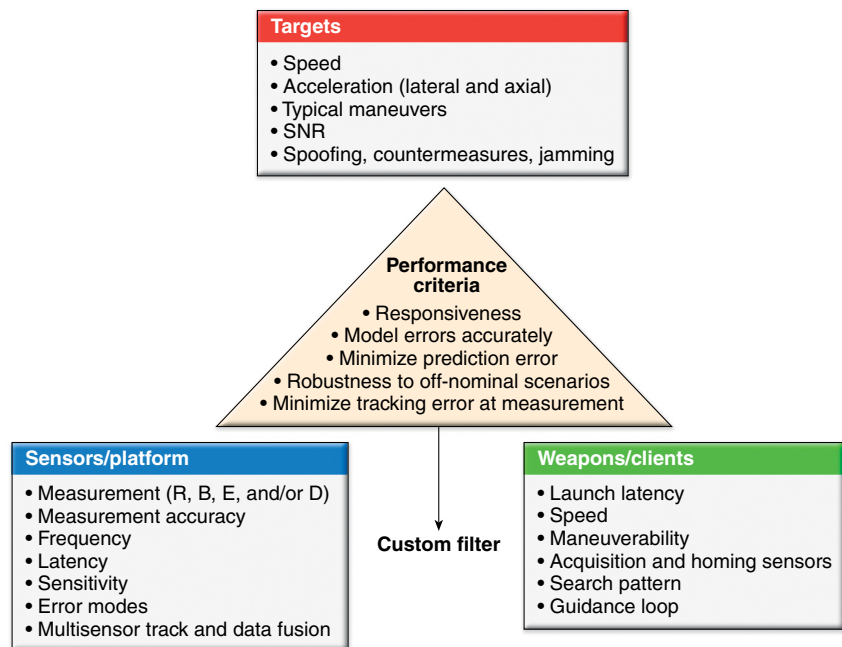
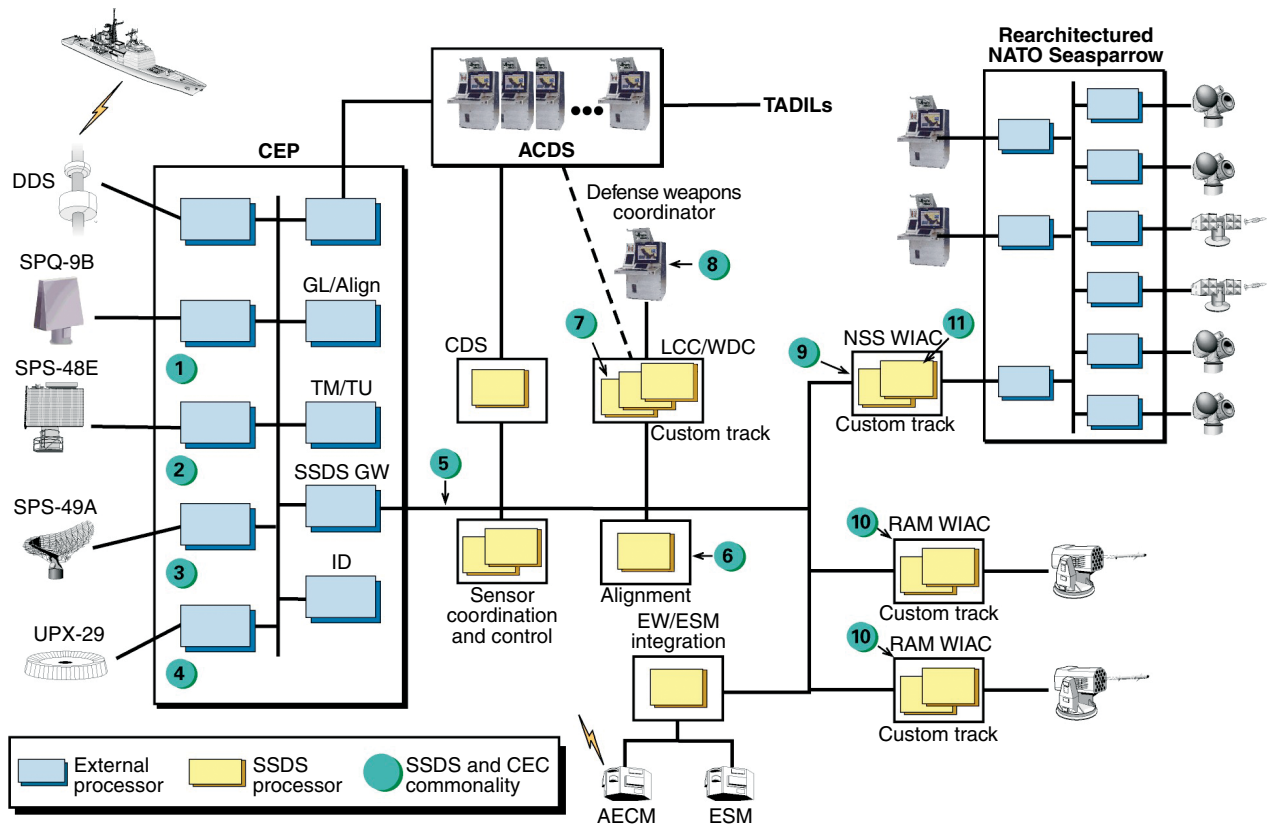


Figure 4. Elements of filter models, together with performance criteria.



**Figure 5.** An SSDS platform: sensors, weapons systems, and CEC.

for CVN-68, depicts some of the elements of Fig. 4 in more detail, while illustrating the functional intersection of CEC and the SSDS custom filter.

The custom filter combines data from remote sensors and the four local sensors shown in Fig. 5. The AN/SPS-49A is a long-range surveillance radar with a 5-s rotation period, Doppler measurements, and a coarse estimate of elevation realized by dithering the beam pattern over the target on successive scans. The AN/SPS-48E is a Doppler radar with a 4-s revisit, electronically scanned in elevation. The AN/SPQ-9B is a surface-scanning Doppler radar with a 2-s period that can be increased to 1 s on designated targets in “look-back” mode. The NSSMS Mk 9 TI is a continuous wave target illuminator, with range, bearing, elevation, and Doppler measurements. Each has limitations: the AN/SPQ-9B cannot see targets at significant elevation; the AN/SPS-48E may not get Doppler estimates on some targets; the AN/SPS-49’s long revisit period makes it difficult to track highly maneuverable targets; and the continuous wave NSSMS/TI can only track a single target and is susceptible to electronic countermeasures.

The custom filter supports two weapon systems—NSSMS and RAM—as well as engagement scheduling. For NSSMS, the TI may occasionally be unable to close its tracking loop due to loss of signal-to-noise ratio during target fades; or it could be jammed or

deceived. During these periods, the TI may go into a slave mode where it is commanded to a pointing position to maintain RF energy on the target of interest. The custom filter’s requirement in this instance is to maintain pointing accuracy. This means minimizing tracking state lag during target maneuvers while minimizing the random errors characteristic of responsive filters.

Unlike the Seasparrow, which closes its control loop at launch and rides the reflected RF signal all the way in to the rendezvous with the target, RAM is launched toward the target but relies upon search and acquisition by its infrared (IR) sensor when used in its Autonomous IR mode. During the time between launch and the initiation of IR search, RAM flies blind. For the inbound targets, which RAM is required to engage, the requirements imposed upon the filter are accurate, instantaneous pointing—as with Seasparrow—but also an accurate representation of the estimation errors for establishing the size and shape of the IR search pattern. During search, the instantaneous field of view of the RAM IR sensor is scanned through either a horizontal or vertical “racetrack” or in a circle. Deciding which pattern to use and sizing it to acquire the target at a prescribed level of confidence are critical to closing the missile homing loop as soon as possible. Further minimizing RAM’s look angle to the target after the latency between launch and IR

scan initiation will levy an additional filter requirement of minimizing the velocity and angle rate errors that integrate into position and angle errors during RAM flyout.

The Mk 2 filter is designed to handle stressing threats. Two in particular deserve mention. The first class is weaving targets that present a challenge to the standard linear Cartesian state space models commonly used. The typical assumption of constant target velocity can lag a maneuvering target significantly between measurement updates, especially if those updates are at a low frequency relative to the target maneuver period. This effect is most pernicious when the weaver appears to be crossing; the linear constant velocity filter tends to extrapolate the target outbound when it has, in fact, turned back inbound. The second class of targets of particular interest is divers (and climbers). Another weakness of constant velocity models is that they tend to be somewhat unstable in the vertical channel. This instability is due to the  $z$  estimates that are determined largely by the radar's relatively noisy elevation angle measurements. When elevation is differenced to infer the vertical rate, the estimate is noisier still. The rate errors integrate in vertical position errors that tend to oscillate due to coupling with other states. This can present problems for determining when a climbing target has leveled off or when a level target has begun its dive to the defensive ship. These target dynamics in the vertical channel, in turn, have implications for NSSMS TI pointing commands and especially for RAM IR search pattern selection.

### Design Approach

The SSDS Mk 2 custom filter combines a number of formal and *ad hoc* filtering practices to create a filter that is simultaneously stable and responsive and is realized at a computational burden manageable to the SSDS signal processing boards.

The fundamental structure of the custom filter is a two-model Interacting Multiple Model filter: a high-maneuver model and a low-maneuver model. Outside 15 nmi, both target models are linear, Cartesian, and of constant velocity. The high-maneuver model provides a higher gain by modeling a target with greater random acceleration.

In parallel with the filter operation, the measurements are continuously fit with a cubic spline. The cubic spline provides a third-order polynomial fit to the measurements, with a different polynomial for successive epochs of data. The epochs

are joined at a node where the polynomials are constrained to be continuous and continuously differentiable. The low order, coupled with these regularity conditions, produces a reliable indication of when the current measurement epoch evinces a change from the last, indicating the target has maneuvered. At the same time, the fit indicates when no maneuver has occurred. When a target turn is recognized, the low maneuver filter target process noise is increased, the state estimation error covariance is decorrelated, and the filter estimate is reset with the values obtained from the current fit. Conversely, when the target is not maneuvering, the gain of the low-maneuver filter is reduced. A heavily filtered track is important for quiescent targets, especially for those inbound. Even with Doppler, the velocity estimates can be quite noisy because velocity orthogonal to the line of sight is inferred by differencing the relatively noisy angle measurements (bearing and elevation). A low-gain filter ameliorates the effect on the target's heading.

Similar nonparametric tests are used in the vertical channel. If a fit through the measurements indicates the target is flying level relative to the elevation measurement uncertainty, the vertical rate estimate is set to zero and the vertical channel is decorrelated from the horizontal channels. This relieves the tendency of the poorly observed vertical estimate to oscillate.

### Implementation

The custom filter comprises three functions shown in Fig. 6. The "store data" function maintains the composite tracks, ship/platform data, and track and measurement histories. The "select and characterize" function selects the best data, determines a kinematic ID by comparing stored data to *a priori* maneuver hypotheses, then

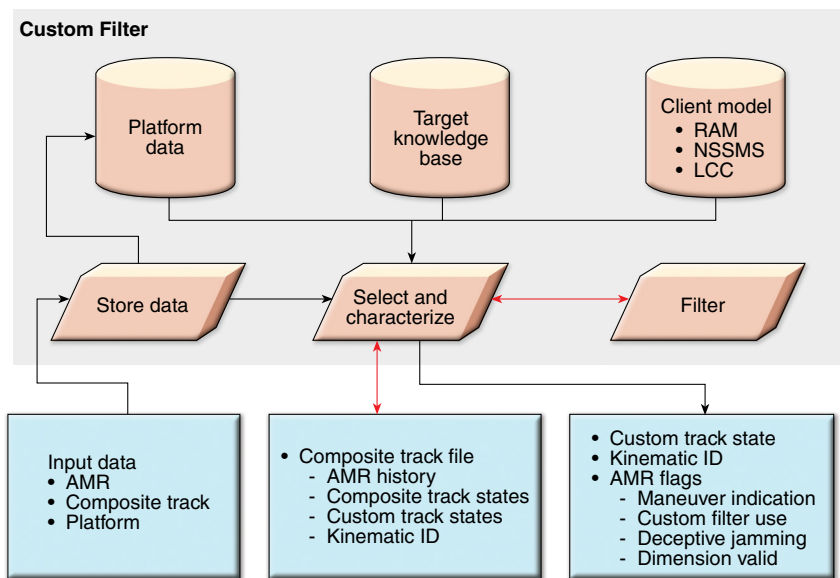


Figure 6. Functional architecture of the SSDS Mk 2 custom filter.



optimizes the filter for that kinematic ID and client. The “filter” function includes the Interacting Multiple Model and each of the contributing filter models.

The custom filter is implemented in C++ as a set of classes that can be customized and reused for other applications in the future. There are three SSDS Mk 2 software components (SCs) that use the custom filter: local command and control (LCC) SC, RAM integration SC, and NSSMS integration SC. The RAM integration SC and NSSMS integration SC use the filter state to provide target position during engagements. The LCC SC uses the filter state in scheduling engagements. The filter was designed so that a single implementation is used by all three SCs. Customization parameters allow the filter to be tailored for each SC while using the same implementation. To minimize the dependence between the SCs and the filter code, the filter was designed so that a single class provides the interface through a set of function calls. Figure 7 shows the interface between an SC and the custom filter.

### System Track Promotion

The mean time between false engagement requirements for combat systems is very long—much greater than the expected lifetime of the combat system. In SSDS, a multisensor method to prevent engagement of false tracks was developed that uses the CEC-provided initial MTBFT and the  $P_{fa}$  for a sensor on a particular track to compute a system MTBFT track quality. Automatic engagements are not allowed on tracks that do not exceed a track quality threshold specified in the engagement doctrine. The system track quality is initialized using the MTBFT reported by the originating sensor tracker. At each update, the track quality is incremented as a function of the  $P_{fa}$  provided by the sensor tracker in each associated measurement report. Similarly, decrements occur as a function of the number of missed detection opportunities for each sensor.

Figure 8 demonstrates this concept for system track promotion. Sensors provide detections to the local track function (in CEC or SSDS). The local track functions perform the association process with system tracks or initiate new local tracks with the unassociated detections. The associated detections along with the  $P_{fa}$  are sent as AMRs to update the system track. The  $P_{fa}$  is based on the size of the association windows and the recent history of occurrence of false contacts from that sensor in the region of the update. Updates occurring in a region of low activity will have a low  $P_{fa}$ , which will result in a larger increment to the system MTBFT. Updates occurring in a region of high activity will have higher  $P_{fa}$ , resulting in a smaller increment to the system MTBFT. New local tracks formed from the unassociated detections are sent with their initial MTBFT to start new system tracks as soon as they meet specific disclosure requirements. This method allows promotion using data from different sensors with very different operating environments and data rates. Normalization is accomplished through the real-time computation of the probability that a false hit could fall into the association window used by the local tracker, based on the association process used for that sensor and the environment measured by that sensor.

Figure 9 shows a typical system MTBFT track quality promotion for a larger and slower threat on the right and a smaller, faster, and lower threat on the left. Vertical lines show the required times (in an engagement sequence) for operator initial alert, recommendation for engagement, and actual order for engagement. Before system engagement of a threat, the MTBFT track quality needs to exceed the threshold for auto hardkill or the engagement recommendation/quick reaction threshold (when conditions allow this lower MTBFT threshold to be set). The graph illustrates how tracks supported by high-quality updates, or multiple sources, reach the quality necessary for engagement actions faster than

tracks supported by lower-quality updates. To maintain effective operation in nonbenign environments and achieve timely engagement of stressing threats, SSDS performs a handoff of threat tracks to fire control radars to quickly attain requisite track quality.

### AN/SPQ-9B Lookback Requests

SSDS can request CEC to utilize the AN/SPQ-9B lookback capability on tracks deemed potential threats to ownship. The AN/SPQ-9B radar antenna consists of two rotating slotted arrays mounted back-to-back

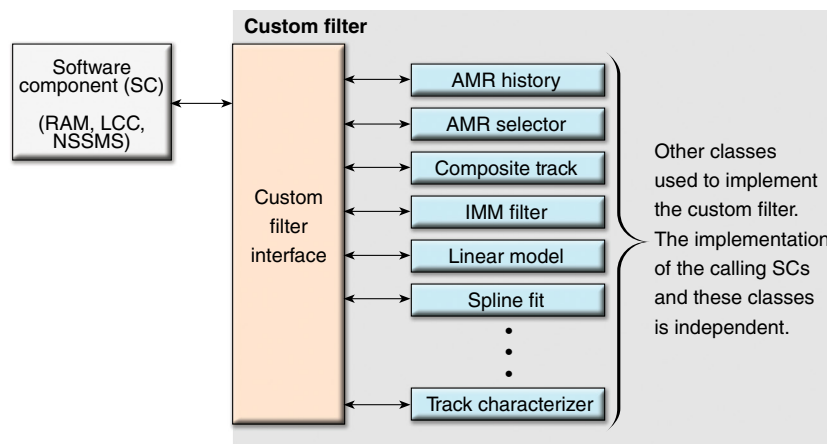


Figure 7. Software component interface with custom filter.

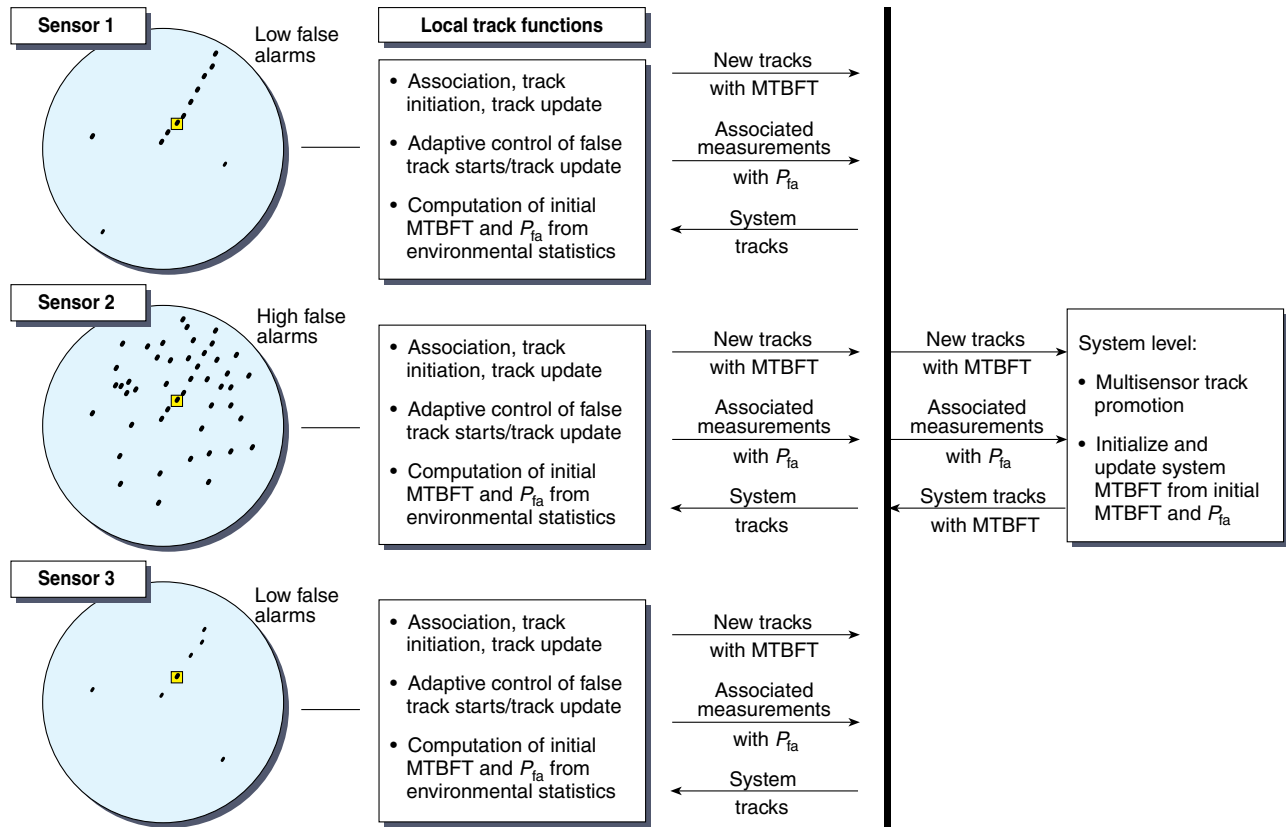


Figure 8. System track promotion concept.

(Fig. 10). The radar transmits a waveform optimized for the radar’s air channel from the front array face and a waveform optimized for the radar’s surface channel from the opposite face. When a lookback request is made for

a particular track, surface channel dwells are replaced by air channel dwells when the face normally used for the surface dwells is pointed at the track, doubling the update rate on that track. SSDS automatically selects and prioritizes targets for lookback service, based on time-to-go, real-time need for the increased data rate, and evidence that the target is in the coverage region of the radar. Figure 11

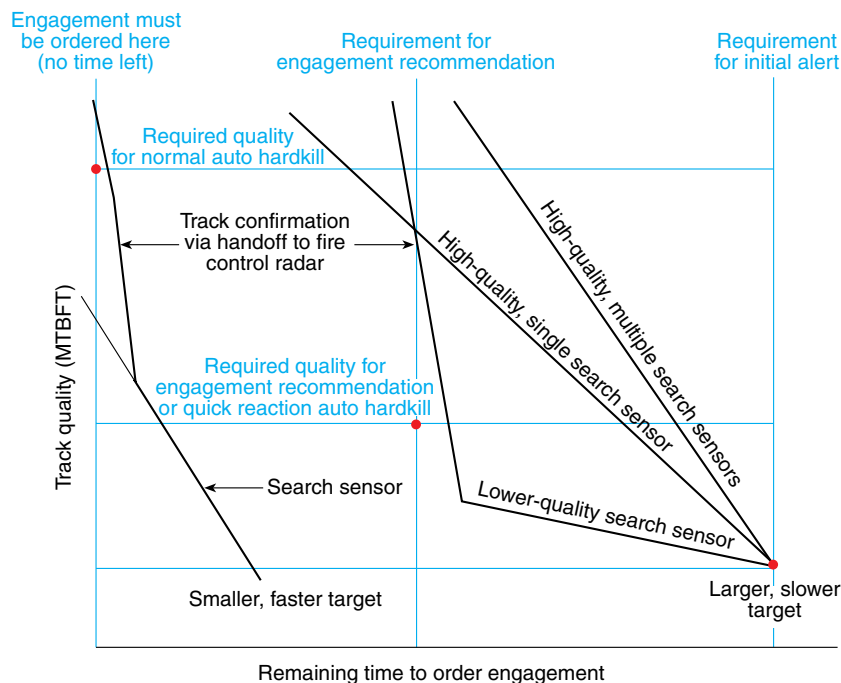


Figure 9. System track quality promotion for different levels of sensor support.



Figure 10. AN/SPQ-9B lightweight back-to-back slotted array antenna. (Photo courtesy of Northrop Grumman.)

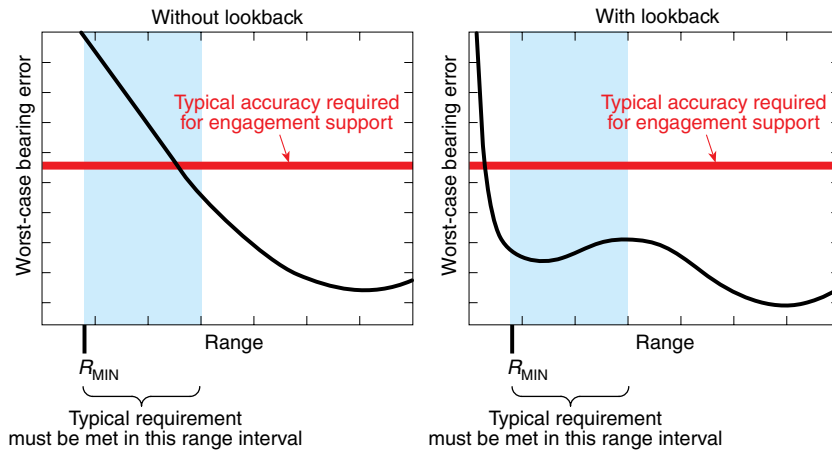


Figure 11. Custom filter bearing error without and with lookback.

shows the accuracy improvement against a weaving air target when lookback is invoked.

### AN/SPS-49A Upspot Request

SSDS can request CEC to provide AN/SPS-49A high diver coverage capability for a track by making it upspot eligible. Eligibility is determined from tactical information, including time-to-go, need for the additional sensor data (such as supporting Mk 9 illuminator pointing), availability of data (lack of elevation coverage from another source), and evidence that the target is at a high elevation angle (not detected by AN/SPQ-9B). The process considers both observed coverage (in real time) as well as *a priori* information about mast blockage regions. For example, the AN/SPS-48E radar has mast blockage over part of its coverage volume. In these regions, elevation data from the 48E can be corrupted, even though the target is still detected by that radar. So, in the 48E mast region, SSDS will request AN/SPS-49A high diver coverage even when 48E data are available. In other regions, SSDS will not request high diver coverage if 48E data are available.

### IFF Interrogation Strategy

SSDS can request CEC to provide IFF interrogation of targets

that are about to be engaged to give friends a last opportunity to respond. A friend may not respond if it is in a propagation fade region. The length of time spent in a fade depends on propagation conditions, the aircraft speed, and its altitude. The goal of the IFF interrogation strategy is to provide at least three interrogations, when sufficient time exists, while guaranteeing that not all three are in a fade region. If the IFF antenna were the traditional rotating “hog trough,” this would be a simple process of interrogating on each sweep past the target. But, in CVN 68, the antenna is a toroidal array, and interrogations can occur almost as fast as desired. Thus, a process must decide when sufficient time has been allowed to exit a fade region. SSDS specified an interrogation strategy that determines the interval based on certain target trajectory parameters in order to minimize the time between interrogations, limit excessive interrogations, and still guarantee that not all interrogations are in a fade region.

### SSDS-CEC INTERFACE AND IDDS

References 2 and 3 are the Interface Description Documents (IDDs). Physically, the interface is a Fiber Data Distribution Interface (FDDI) local area network (LAN). Transmission Control Protocols (TCP) and User Datagram Protocols (UDP) are used to establish connections over the FDDI LAN. In addition, for SSDS Mk 2 Mod 1/2, there is a separate Ethernet interface that uses TCP. Figure 12 shows the connections and the types of data being sent across each connection. A UDP socket is created over the FDDI interface for the transfer of time synchronization data from SSDS to CEC. A TCP socket is established over the FDDI for the transmission of

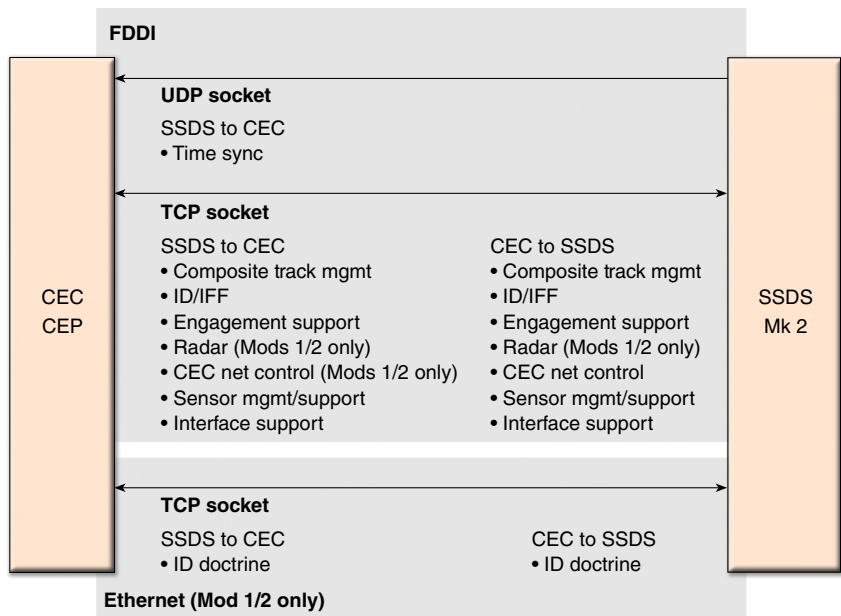
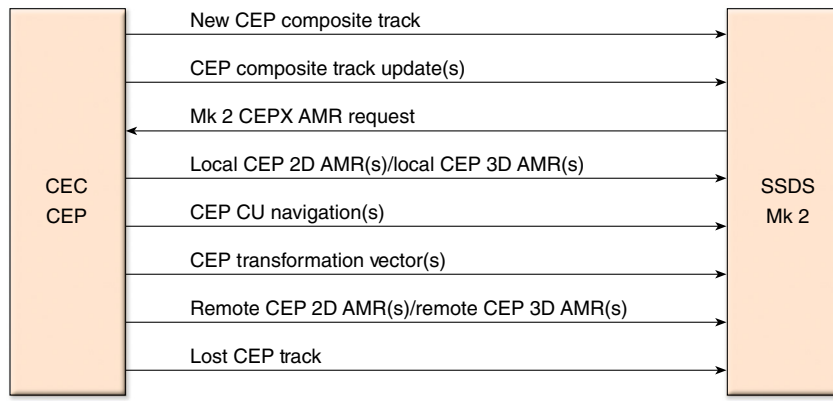


Figure 12. CEC-SSDS interface.



**Figure 13.** Custom filter message sequence in the CEC-SSDS interface.

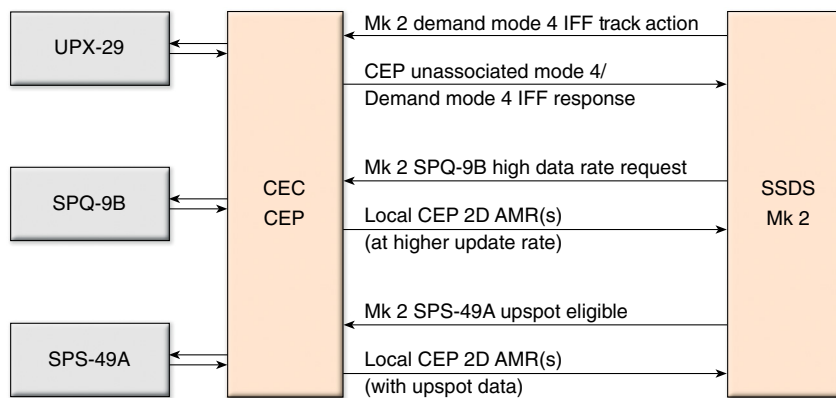
other data between CEC and SSDS. A TCP socket is also created over Ethernet for the transfer of ID doctrine control and status data. Figure 13 provides an example of the sequence of messages sent over the interface that supports the custom filtering functions in SSDS. There were concerns that the number of AMRs within CEC would overload the interface to SSDS, so messages were defined to allow SSDS to request AMRs as needed. In addition to providing AMRs to SSDS, the interface provides several other messages that allow SSDS to request additional data from CEC sensors to support self-defense functions. Figure 14 provides examples of some of these messages.

### NSSMS INTEGRATION

The SSDS integration with NSSMS is a major advancement that provides support of both RAM and NSSMS engagements, improved CEC track continuity, and improved resistance to degradation from propagation fades, RF deception, or target maneuvers. Engagement of targets with the Seasparrow Missile requires illumination of the target by the Mk 9 TI. The system was originally designed to receive a target designation from an external source, which it would use to search and acquire that target with the Mk 9 TI. Once acquired, the system tracked and illuminated the target solely on the basis of Mk 9 radar data. A slave illuminate capability using external track data was provided, but TI measurement level data were not available to support the external track. This approach has some limitations, which include potential

loss of the track due to RF propagation fades or jamming, susceptibility to RF deception, and difficulty in separating targets if more than one target is in the beam.

The SSDS Mk 2 integration approach overcomes these limitations and provides major benefits. As before, NSSMS can accept designations from the external system (SSDS). SSDS selects the NSSMS acquisition pattern based on track accuracy to minimize acquisition time. However, NSSMS is no longer solely reliant on the TI track after acquisition. A critical new NSSMS feature is the capability to recognize a track fade and to automatically start using the SSDS track data to keep the illumination beam on the target. Furthermore, when NSSMS is detecting the target, it provides SSDS with measurement level data that can be incorporated in the custom filters to provide a multisensor-based track that is optimized for engagement support. This track not only supports engagement with NSSMS but RAM as well. Using very accurate range and Doppler range rate measurements from the low data rate surveillance radars and high data rate angle and Doppler measurements from the Mk 9 TI, the multisensor track is much better than would be possible from either source alone. SSDS performs association processing of Mk 9 data with the CEC composite track state and provides the updates both to SSDS for custom filtering and to CEC for composite tracking. SSDS is specified to include processes that detect conditions where the Mk 9 data could be corrupted and to (1) prevent these data from getting to CEC, (2) prevent these data from corrupting the custom filter states, and (3) maintain NSSMS illumination during the corrupted condition by automatically switching to the slave mode. These conditions include RF deception and conditions where multiple targets create an ambiguous result.



**Figure 14.** Examples of custom filter messages in the CEC-SSDS interface.

## ALIGNMENT CONCEPT

To integrate SSDS with CEC, all aspects of alignment including sensor bias errors, offsets, gridlock, reporting frames of reference, data definitions, and refraction corrections were examined. Allocation of alignment requirements was reviewed and refined such that the alignment of designation data to the weapons was ensured. In SSDS Mk 2, CEC is responsible for calculating and correcting the range, bearing, and elevation alignment biases between the AN/SPS-48E, AN/SPS-49A, AN/UPX-29, and AN/SPQ-9B. SSDS is responsible for calculating the self-defense alignment biases between that aligned set and the four NSSMS directors. This approach depends on other shipboard procedures to ensure that the weapons (RAM and NSSMS) are aligned with the fire control radars. Once this is done, the process ensures complete alignment between sensors and weapons. To enable correct use of CEC remote measurement data by SSDS, CEC determines the gridlock solution and provides SSDS with a remote transformation matrix and the remote cooperating unit's (CU's) navigation information. The transformation matrix and navigation data provide information such as coordinate conversions and the remote unit's heading, pitch, and roll. With this information, SSDS can properly use CEC remote measurements in its custom track filters.

## HUMAN-MACHINE INTERFACE CONCEPTS FOR SELF-DEFENSE

A high-quality Human-Machine Interface (HMI) is essential for successful combat system integration. The self-defense paradigm for combat system architecture is often depicted as a classic detect-control-engage sequence, where combat system operators are almost a peripheral element of the control function. Yet, from the perspective of those who operate the combat system on a daily basis, the HMI provides the most visible evidence of successful combat system integration. Significant effort was dedicated to ensuring that the advancements in automation could be used by the operators with ease and confidence. The three goals established for the design of the self-defense HMI were to (1) only show the operator important and relevant status, (2) design interactions so that the operator can quickly decide what to do and not spend time on how to do it, and (3) automate controls so that minimal operator intervention is required.

To meet the HMI design goals, it was necessary to depart from styles typically used for radar controls. Previously, controls took the form of tables of parameter settings where the operator could type new values or select settings from pop-up menus (Fig. 15). This violates the first two design goals. It requires the operator to understand many different parameters and how their settings

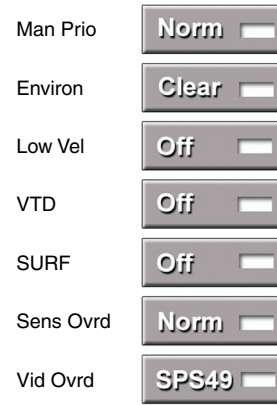


Figure 15. HMI old-style pop-up menus.

interact and includes parameters that do not affect the final result. Instead, SSDS HMI emphasized visual representation of state and direct manipulation. Visually representing the radar state through symbols and colors allows the operator to quickly examine it and to easily notice changes without having to read numbers and recall their significance. Direct manipulation combines visual representation of parameters with the ability to change them to see the immediate effect of the change.

Implementation is divided into three parts: sensor status, operational context, and sensor controls. Sensor status is displayed using colored icons to show the operational status of the radar and the overall influence of the self-defense parameter settings. The operational context of the sensor is shown through the use of graphical overlays on the tactical picture that allow the operator to see the effect of the parameter settings. The sensor controls are implemented as simple sliders that present the various combinations of available self-defense parameter settings as a linear sequence of choices for a simplified concept of sensitivity. The slider control setting is enabled in range and bearing sectors.

To provide a visual representation of the status of the radar and the influence of the self-defense settings, a system of color-coded icons was developed. The icons shown in Fig. 16 allow the operator to determine the overall status of each sensor at a glance. They depict the data flow from the radar antenna to the tracker. Each icon indicates the status of a critical step of the process and the influence of self-defense parameter settings on that step. The icons (groups of three as shown in the figure) read from left to right. The first icon (radar emissions) shows the gross ability of the radar to make detections. In addition to showing whether the radar is actually on and radiating, it shows the influence of any sectors that have been entered to block radiation. The center icon (interface) indicates whether the interface between the radar and the tracker has been enabled. This icon will indicate a degraded state if any sectors have been entered that decrease the sensitivity of the radar. The right icon (composite tracking) indicates

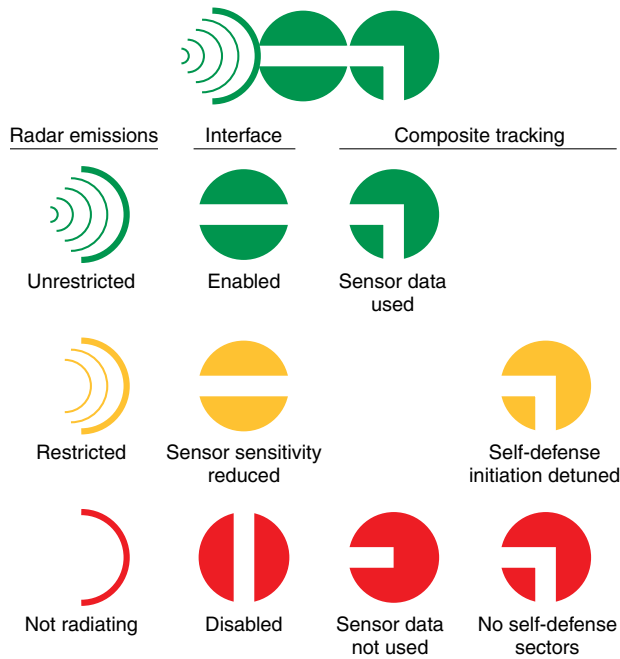


Figure 16. HMI icons.

whether the contributions from the sensor are being used. It also shows when the settings for track initiation have been altered from the default settings.

The self-defense parameters of the radar control the sensitivity of the radar and its ability to track targets. The system includes a high level of automation that has been proven operationally to adapt to most environments so that the operator is rarely required to adjust the radar sensitivity. As a safeguard against unexpected environments, the operator is provided with the capability to adjust the self-defense parameters. The parameters can be altered in sectors. A collection of parameters in a sector is adjusted by a simple slider control (Fig. 17) that maps sector settings to sensitivity values. To provide the operator with a means of observing the operational context in which the radar is operating and to determine whether action is required to mitigate the effect of the environment, a visualization of the environment is shown to the operator through a geographic data display. The location of the ship is indicated on a map background over which is laid a visual representation of the radar contacts. Each contact is displayed as a dot at the location of the detection. By observing



Figure 17. SSDS sensitivity slider control.

the clustering of the contacts, the operator is able to determine if and where it is necessary to modify the self-defense parameters.

## SUMMARY

With requirements development and allocation and most detailed design completed, the SSDS Mk 2 and CEC 2.1 programs are moving ahead on two fronts. The configurations exclusively for the USS *Nimitz* (CVN 68) combat system, comprising SSDS Mk 2 Mod 0 and CEC 2.1a, have been initially coded, developer tested through formal qualification testing, brought under U.S. Navy configuration management, and installed in CVN 68. These versions are now undergoing Navy-directed integration testing both at the land-based Surface Combat Systems Center at Wallops Island, Virginia, and aboard *Nimitz* before final approval for Fleet use. Initial tests have proven the SSDS-CEC integration approach. The follow-on configurations for CVN and LPD 17 class ships, comprising SSDS Mk 2 Mods 1 and 2 and CEC 2.1b, are concluding detailed design and progressing through software coding. Early software build testing is being conducted on the developer's software testbed using wrap-around simulation programs. These versions represent an even tighter integration of SSDS and CEC as all the sensor control HMI is implemented on the SSDS consoles.

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