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Integration of Electronic Support Measures (ESM) and Alpha-Beta Radar Tracker

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By

K. H. Kim

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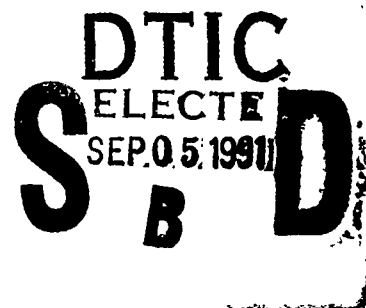
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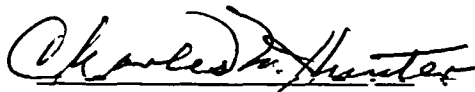
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13. ABSTRACT (Maximum 200 words) In target environments that include Electronic Countermeasures (ECM), where availability of radar range measurements is severely reduced, an integration of ESM data into a multi-sensor tracker provides an inexpensive but effective approach to augmenting radar tracking systems. Tracking-filter equations are presented for a multi-heterogenous sensor tracking system consisting of radars and ESM sensors. Measurement time-based track updating is performed, due to non-periodicity of ESM measurement acquisition times, instead of the usual track-based updating times. Track updating, using ESM measurements, is accomplished via an extended Kalman filter (EKF)-based algorithm and radar measurement via an α - β tracking algorithm. The integration of data from different sensor types is a logical response to increasingly hostile airborne threats. The technique described in this paper is a straightforward and cost-effective approach for accomplishing that integration.				
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The angle-of-arrival (AOA)-AOA ESM tracker design and simulation, which served as the basis for the integrated radar-ESM tracker, was conceived in collaboration with T. M. Hart of The MITRE Corporation.



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INTRODUCTION

This report contains an annotated briefing presented at the 1990 Society of Photo-optical Instrumentation Engineers (SPIE) Technical Symposia on Aerospace Sensing Conference for Signal and Data Processing of Small Targets. The conference was held in Orlando, FL from 16 to 20 April 1990.

Integration of Electronic Support Measures (ESM) and α - β Radar Tracker

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The MITRE Corporation

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Integration of Electronic Support Measures and α - β Radar Tracker

There is an increasing utilization of passive sensors in multiple target tracking. This paper describes a method of integrating electronic support measures (ESM) and an existing α - β radar tracker. The method can be generalized to address different types of ESM measurement data and different radar trackers.

Motivation

- **Reduced availability of radar measurements in electronic countermeasure (ECM) and low observable environment**
- **ESM-targetable emissions may be available during periods of interrupted track updates**
- **Identification information derived from ESM data for track-data association (Not addressed here)**

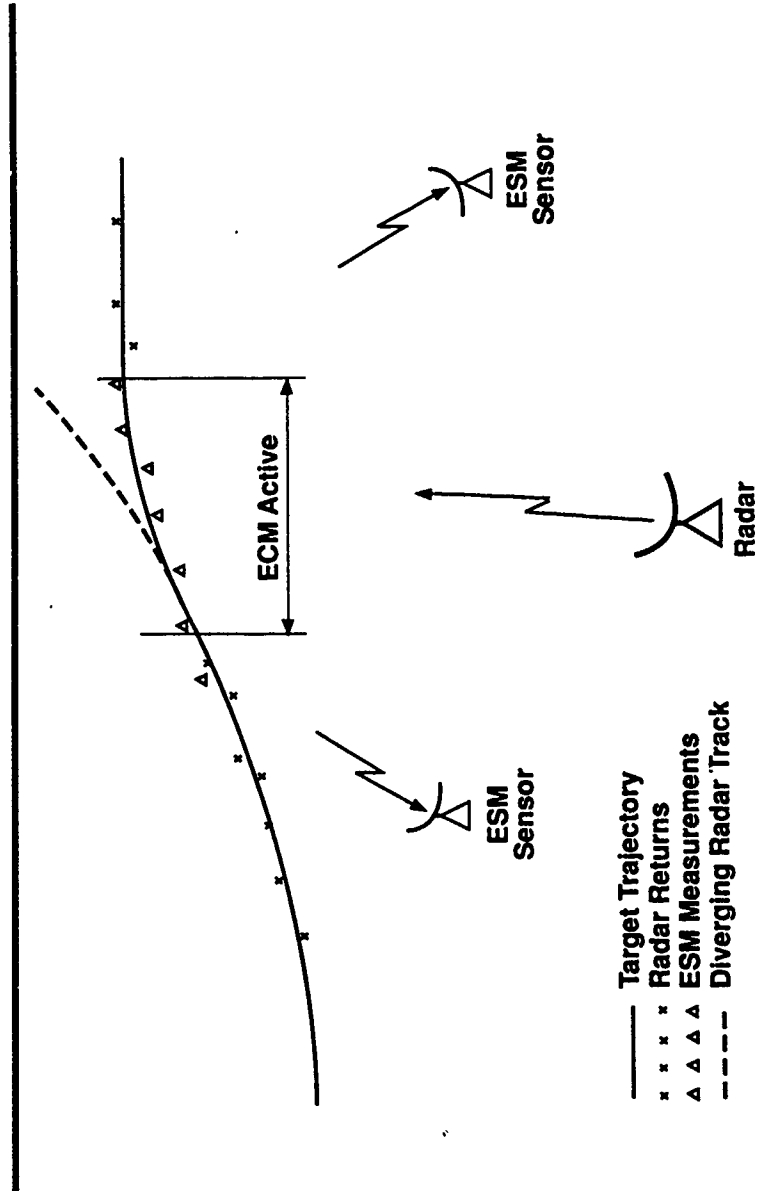
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Motivation

In target environments where the availability of radar range measurements is severely reduced due to several possible factors including electronic counter measures (ECM), terrain screening, and the presence of low radar cross section targets, augmenting the radar tracking system with an ESM tracker provides an inexpensive but effective approach to improving track maintenance.

An ESM sensor is a passive sensor used to detect emissions from platforms containing signal emitters such as ECM devices and acquisition radars. In addition, it also provides non-kinematic target ID information which can be utilized for data association.

Scenario



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Scenario

This figure shows a hypothetical tracking scenario where the solid line represents a true target trajectory, x's denote radar returns, and Δ 's indicate measurements from the two ESM sensors, both of which are detecting emissions and providing reports during the scenario.

When an ECM device is activated, the range measurements may become too degraded to achieve reasonably good tracking performance with a radar tracker alone, as depicted in the figure by the diverging radar track.

During this period, the ESM tracker can take over the task of updating tracks and provide continuity in track maintenance.

Problem Statement and Limitation of Scope

- **Augment α - β radar tracker with an ESM tracker**
- ● **Need to generate covariance matrix for α - β tracker**
- **No consideration of track/ESM data association**
- **No algorithm for detection ECM activation/deactivation considered**
- **No false alarms considered**

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Problem Statement and Limitation of Scope

Track fusion techniques can significantly benefit from the use of a state estimation covariance matrix to rationally combine data of different dimensionality and quality. Unfortunately, α - β trackers such as the one being employed in this analysis do not provide this mechanism. Thus, we need to generate the covariances using the smoothing gains α and β .

To simplify the task, we do not consider how track/ESM data association is performed, the algorithms to detect ECM activation/deactivation, emission mode changes, and false alarms.

Overview

- **Review of stationary target location techniques and performance measure**
- **Review of trackers**
 - **Radar trackers**
 - **ESM trackers**
- **Integration of trackers**
- **Simulation results and discussion**
- **Future work**

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Overview

For the tracker integration, we use the centralized approach to fusion where all the sensor measurements are sent to a central processing site to create/maintain system tracks.

One of the problems with this method is that low quality measurements from one sensor can lead to poor system track quality. Therefore, we need to establish baseline sensor requirements by analyzing target ranging techniques. After that, we will briefly review the extended Kalman filter (EKF) equations used for ESM trackers and describe a tracker integration method. Computer simulation results and discussion will be followed by a description of future research work.

Review of Location Techniques

- **Radar**
 - Range, azimuth from one sensor
- **ESM triangulation**
 - Angle of arrival (AOA) from two sensors
 - Location calculated from intersecting strobes
- **ESM trilateration**
 - Time difference of arrival (TDOA) from three sensors
 - Location calculated from intersecting hyperbolas
- **ESM AOA/TDOA**
 - AOA from one sensor and TDOA from two sensors
 - Location calculated from intersecting strobe and hyperbola

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Review of Location Techniques

Let us review various target location techniques. The most obvious one is target location by using radar measurements in which both range and azimuth information are contained in a single report.

If angle of arrival (AOA) measurements are available from two or more spatially separated angle sensors, target location can be determined from the intersection of strobes.

If ESM sensors are capable of measuring signal arrival times, then using the time difference of arrival (TDOA), target location can be determined from the intersection of hyperbolas since the constant TDOA curve is a hyperbola.

If a system consists of mixed sensors, i.e., AOA and TDOA, the location is determined by intersection of a strobe and a hyperbola.

One of the problems in the passive ranging techniques is asynchrony in measurement acquisition! that spatially separate sensors may not be able to detect the same signal at the same time, and the time asynchrony will result in location estimate errors.

Performance Measure

- Size of the minimum area having a specified probability of containing the estimate
- Elliptic shape under Gaussian assumptions
 - Not a good measure if too elongated
- Circular Error Probable (CEP)
 - Radius of a circle representing the specified probability (ex. 50%) region of the estimate

$$\text{CEP} \approx 0.75 \sqrt{\sigma_x^2 + \sigma_y^2}$$

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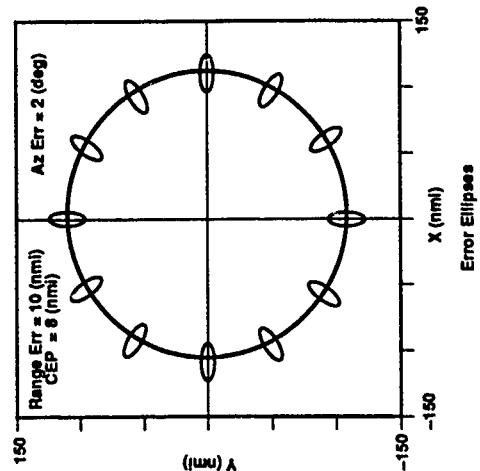
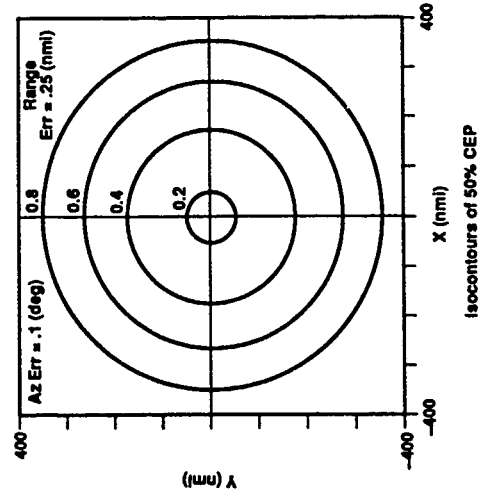
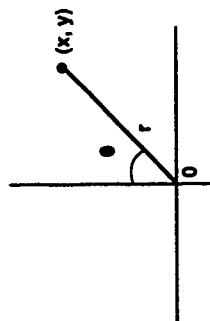
Performance Measure

One common performance measure used to evaluate ranging methods is to specify the size of the minimum area containing the location estimate with a certain probability. If the underlying distribution is Gaussian, the area is a rotated ellipse. But this measure of accuracy has a disadvantage because it can be quite elongated in one direction. An alternative is a circular area, called circular error probable (CEP). CEP is defined as a radius of a circle representing the specified probability.

Calculation of exact CEP is cumbersome and time consuming. Many approximations have been published in the literature, and the most often used expression is shown here.

Target Location by Radar

- Target Position Measured in Polar Coordinate



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Target Location by Radar

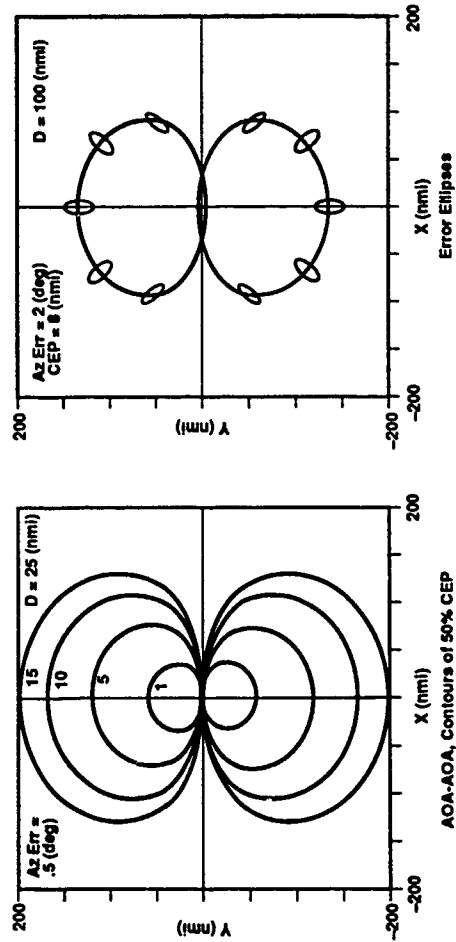
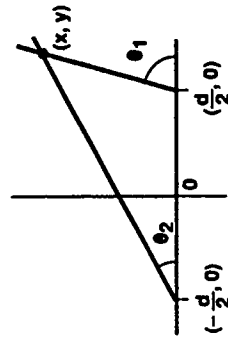
This vugraph shows isocontours of 50% CEP of radar measurements with 0.25 nmi range error and 0.1° azimuth error, one standard deviation. Using a linearized error analysis, we can find that the isocontours are concentric circles centered at the radar site. The CEP circles for 0.2, 0.4, 0.6 and 0.8 nmi position errors are shown on the left-hand side. Note that the isocontours are isotropic, i.e., independent of azimuth.

We can observe that with these measurement errors, the location accuracy is 0.4 nmi up to a range of nearly 200 nmi.

The right-hand figure shows the shape and orientation of error ellipses plotted on an isocontour. The measurement errors have been greatly exaggerated for illustration of error ellipses.

Target Location by AOA-AOA

• Intersection of Strobes



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Target Location by AOA-AOA

In the AOA-AOA targeting method, target location is determined by the intersection of bearing lines as shown in the upper right-hand figure.

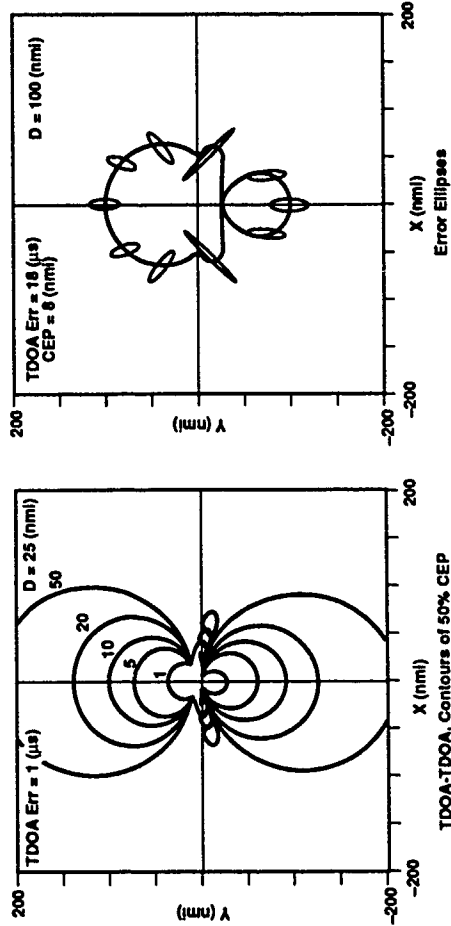
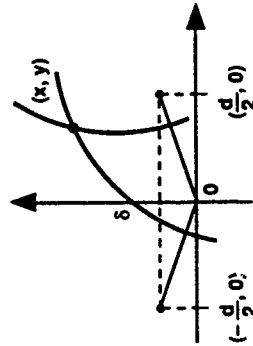
The isocontours of 50% CEP are illustrated in the left-hand figure where the AOA error is 0.5° and sensor separation is 25 nmi. Location accuracy is 5 nmi at a maximum range of 100 nmi. Also notice that there are blind regions near the sensor baseline.

The shape and orientation of error ellipses are shown in the right hand figure.

As stated earlier, a key problem with the AOA-AOA triangulation technique is that both sensors must detect the same signal emission. For spatially separate sensors attempting to detect a narrow bandwidth emitter, the simultaneous detection/measurement of the emission at both sites is unlikely.

Target Location by TDOA-TDOA

• Intersection of Hyperbola



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Target Location by TDOA-TDOA

The TDOA-TDOA method uses time of arrival (TOA) measurements from three or more distributed ESM sites.

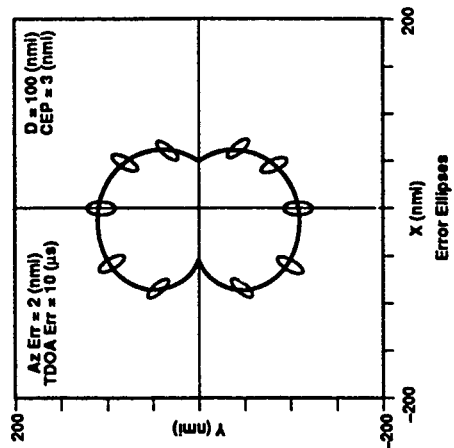
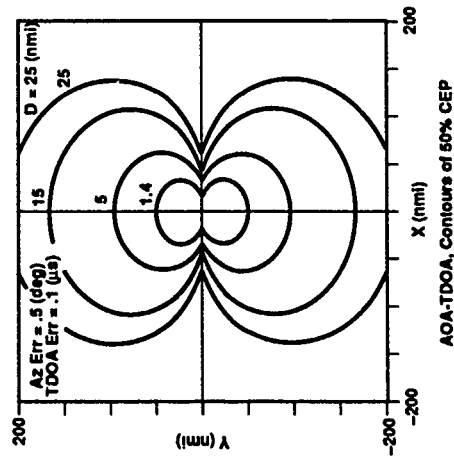
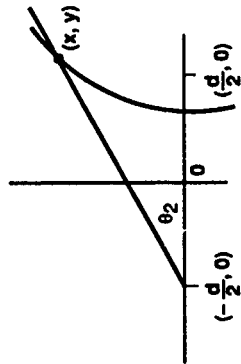
This technique involves pairing the ESM sensors with each other to obtain TDOA measurements, which form in hyperbolas, and calculating the intersection of the hyperbolas as shown in the upper right-hand figure. With a 1 μ sec TDOA time measurement error, one standard deviation, and a 25 nmi forward sensor separation at a 120° subtended angle, the location accuracy is 10 nmi at a maximum range of 100 nmi. Like the AOA-AOA method, there are blind regions in this configuration.

The shape and orientation of the error ellipses are illustrated in the right-hand figure.

The problem of simultaneous time detections/measurements in the AOA-AOA triangulation ranging technique is exacerbated in the TDOA-TDOA technique. Instead of merely needing to detect the same emission, to obtain the TDOA to the accuracy needed, the two (or more) sensors need to detect the same pulse or group of pulses within an emission and be able to determine that each sensor is indeed measuring the same pulse/group.

Target Location by AOA-TDOA

• Intersection of Strobe and Hyperbola



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Target Location by AOA-TDOA

The AOA-TDOA location technique is a two-sensor technique. It requires AOA be measured at one of the two ESM sites. In addition, the TOA at both sites needs to be measured to obtain TDOA. The location is determined by identifying the intersection of the strobe and hyperbola, as shown in the upper right-hand figure.

Isocontours of 50% CEP are shown in the left-hand figure where the azimuth error is 0.5° and TDOA error is $0.1 \mu\text{sec}$. With these measurement errors, location accuracy is 5 nmi at a maximum range of 100 nmi.

The shape and orientation of the error ellipses are shown in the right hand figure.

The time synchronization problem is still formidable with this technique; although not as difficult as the TDOA-TDOA technique in which two pairs of sensors must measure the same pulse group, still, in the AOA-TDOA method, a single pair of sensors must measure the same pulse group and one of the sensors must measure the AOA of that same emission.

Stationary Location Analysis

- **Location analysis provides comparison of different techniques**
- **Mechanism for determining baseline sensor requirements**
- **Provides initial covariance estimates for target tracks**

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Stationary Location Analysis

From the analysis of location techniques, the following conclusions can be made:

1. Due to the time asynchrony in ESM measurement acquisition, measurement-time based track updating is more desirable to avoid extrapolation of measurements to a common track updating time.
2. To achieve radar-comparable location accuracy, the AOA measurement error should be on the order of a degree and the TDOA error on the order of a .1 μ sec.
3. The location analysis can provide initial covariance estimates for target tracks.

EKF Based Trackers

	Radar	AOA	TDOA
Output Equation	$Z(k) = \begin{pmatrix} \sqrt{x^2 + y^2} \\ \tan^{-1}\left(\frac{x}{y}\right) \end{pmatrix} + \begin{pmatrix} \eta_r \\ \eta_\theta \end{pmatrix}$	$Z(k) = \tan^{-1}\left(\frac{x}{y}\right) + \eta_\theta$	$Z(k) = \sqrt{x^2 + y^2} - \sqrt{(x - x_0)^2 + (y - y_0)^2} + \eta_D$
Linearized Measurement Matrix	$H = \begin{pmatrix} \frac{\partial r}{\partial x} & \frac{\partial r}{\partial \dot{x}} & \frac{\partial r}{\partial y} & \frac{\partial r}{\partial \dot{y}} & \frac{\partial \theta}{\partial x} & \frac{\partial \theta}{\partial \dot{x}} & \frac{\partial \theta}{\partial y} & \frac{\partial \theta}{\partial \dot{y}} \\ \frac{\partial \theta}{\partial x} & \frac{\partial \theta}{\partial \dot{x}} & \frac{\partial \theta}{\partial y} & \frac{\partial \theta}{\partial \dot{y}} & \frac{\partial \theta}{\partial x} & \frac{\partial \theta}{\partial \dot{x}} & \frac{\partial \theta}{\partial y} & \frac{\partial \theta}{\partial \dot{y}} \end{pmatrix} \quad \hat{\mathbf{x}} = \hat{\mathbf{X}}$	$H = \begin{pmatrix} \frac{\partial \theta}{\partial x} & \frac{\partial \theta}{\partial \dot{x}} & \frac{\partial \theta}{\partial y} & \frac{\partial \theta}{\partial \dot{y}} \end{pmatrix} \quad \hat{\mathbf{x}} = \hat{\mathbf{X}}$	$H = \begin{pmatrix} \frac{\partial D}{\partial x} & \frac{\partial D}{\partial \dot{x}} & \frac{\partial D}{\partial y} & \frac{\partial D}{\partial \dot{y}} \end{pmatrix} \quad \hat{\mathbf{x}} = \hat{\mathbf{X}}$

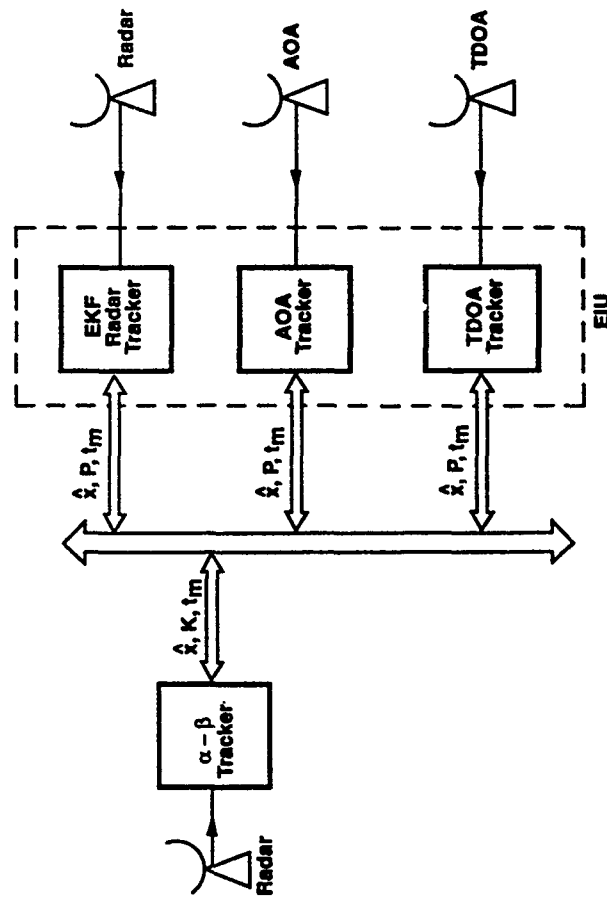
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EKF Based Trackers

The ESM tracker used in this study is an extended EKF whose model is represented by a linear state equation and a nonlinear measurement equation.

In this vignette, measurement equations and linearized measurement matrices are tabulated for radar, AOA, and TDOA trackers. For simplicity, all measurement errors are assumed to be additive white Gaussians.

Tracker Integration Architecture



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Tracker Integration Architecture

A general architecture of an integrated ESM tracker system with various sensors is illustrated in this vugraph. Trackers are tightly coupled through a data bus and data concerning the smoothed track $\hat{X}$, covariance P , and measurement time t_m are exchanged. Depending on hardware limitations, the tracker modules may reside in an interface unit which receives the ESM measurements as indicated by the dashed line. This architecture shows several possible sensor/tracker types; a specific application would likely only contain a subset of these types.

Tracker Integration (Continued)

- **Measurement processing:**
 - **Sequential asynchronous processing (measurement based update)**
 - **Smoothed state vector, covariance matrix, and smoothing time are broadcast to other modules**
 - **Whoever receives next measurement will assume the task of updating tracks and broadcast the updated information**

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Tracker Integration (continued)

The measurements are sequentially processed one at a time. After one measurement is processed, the time-tagged smoothed state vector and covariance matrix are broadcast to all other tracker modules. Regardless which sensor receives the next measurement that correlates with that track, independent of whether it is a radar or an ESM return, that sensor's tracker will assume the task of updating the track. Due to asynchrony of measurement acquisition times, the assigned tracker performs the functions of measurement correlation, prediction and smoothing, as opposed to the classic processing order of prediction, correlation and smoothing.

Tracker Integration (Continued)

- Emulation of variance in α - β tracker
 - Replace standard Kalman update
$$P(k|k) = (I - KH) P(k|k - 1) \text{ with } P(k|k) = (I - KH) P(k|k - 1) (I - KH)^T + KRK^T$$
- $P(0|0)$ obtained from linearized error analysis

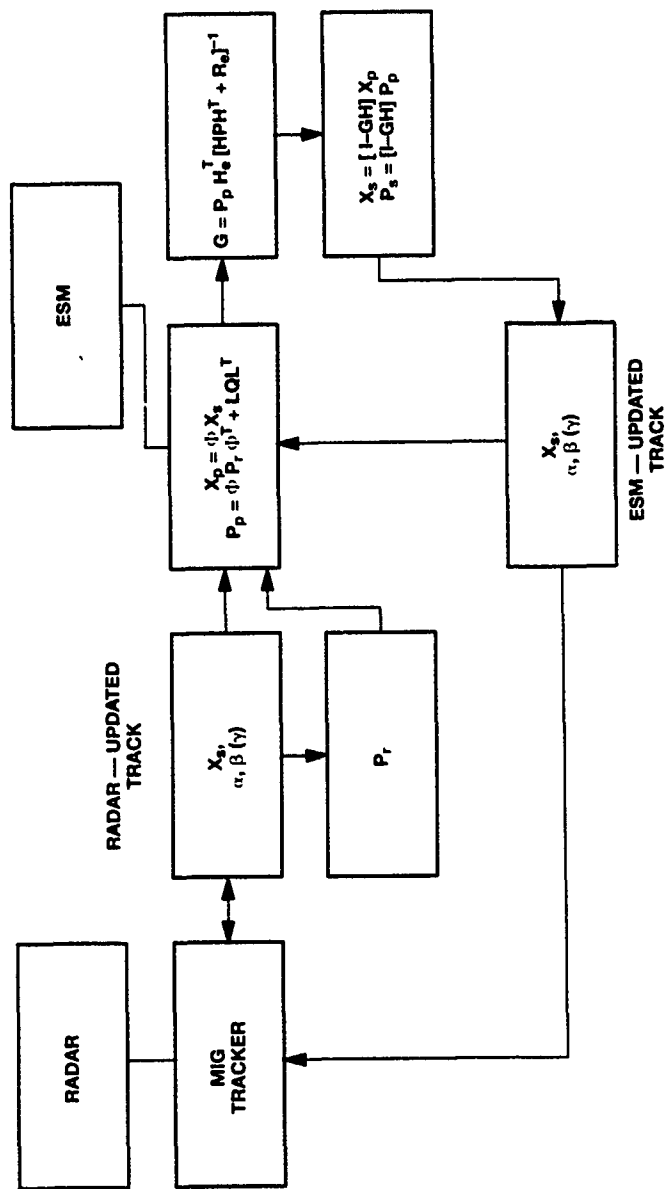
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Tracker Integration (Continued)

Emulation of a covariance matrix for an α - β tracker can be achieved by using a slightly different covariance update equation because the smoothing gains α and β are obtained from a lookup table. The emulated covariance matrix can then be passed to the other tracker modules to be used by the EKF trackers as an input to the track updating process.

The linearized error analysis discussed earlier can be used to compute the initial covariance matrix.

ESM/Radar Tracker



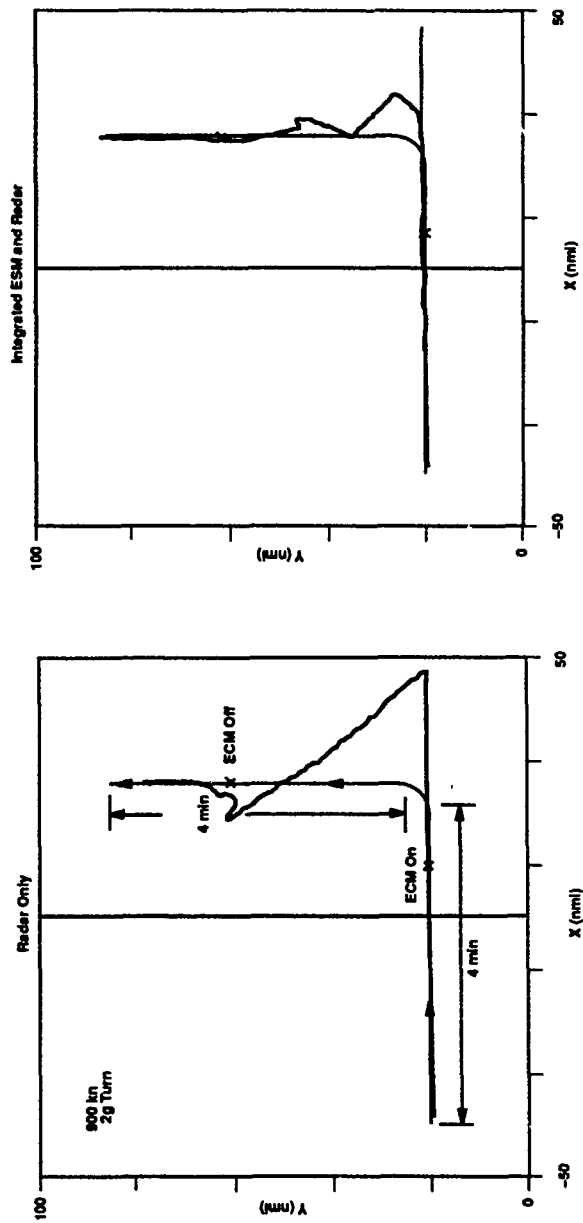
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ESM/Radar Tracker

This vignette summarizes the sequence of data processing in the integrated ESM tracker in which only the α - β radar tracker and the AOA ESM tracker are operational. Assume a track has been established and a radar measurement is acquired. Then the α - β tracker updates the track and the smoothing gains α and β . The smoothed state vector $\hat{X}_s$ and α , β are passed into the ESM tracker module where the emulated (radar tracker) covariance P_r is computed. If the next measurement is an ESM AOA measurement, then the predicted state vector $\hat{X}_p$ and the predicted covariance P_p are computed using the radar tracker covariance. The Kalman gain G is next computed, and the smoothed state is in turn computed.

The smoothed state is fed back to the radar tracker, and α , β can be updated if needed. If the next measurement is a radar measurement, the state is predicted to the radar measurement time and the processing is repeated; if instead an ESM measurement is next acquired, the ESM processing module will be executed.

Simulation Result



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Simulation Result

A computer simulation was developed, and test cases using the α - β radar tracker and AOA ESM tracker run. In the computer simulation, a target travels at a constant speed of 900 knots eastward for four minutes, makes a 90 degree counterclockwise turn with 2 g's lateral acceleration and continues a straight flight northward for another four minutes. Radar target detection probability is initially 0.7 and the radar scan time is 10 sec. ECM is assumed to commence three minutes into the flight and last for a total of three minutes, during which time no radar data is processed for tracking. The response of the α - β tracker is illustrated in the left-hand figure. The single radar is located at the origin. As can be observed, the track continues coasting when ECM is on since no range information is received. In the right hand figure, two ESM sensors are located at coordinates (-10,0) and (10,0). The target probability of detection is 0.9 for the two ESM sensors. The figure demonstrates how, using the ESM AOA data, the maneuver is detected and responded to much more quickly. This scenario illustrates the tracking ability of the ESM-augmented radar tracker.

Discussion

- **Inexpensive but effective approach to augmenting radar tracker**
- **Easily adaptable to existing systems**
- **Improvement in tracking error and track maintenance**

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Discussion

The integration technique is easy to implement and straight forward. It can be easily adaptable to an existing α - β tracking system without rewriting the tracker software. As we have observed, the integrated ESM tracker provides noticeable improvements when the availability of radar measurements is low.

Future Work

- **Complete simulation study of AOA, TDOA tracker integration and analysis**
- **Utilization of ID information for data association**

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Future Work

The test cases analyzed to date have focussed on an α - β radar tracker and a two-site AOA ESM tracker.

We plan to continue the simulation study by examining TDOA tracker integration and analysis, as well as examining performance with a one-site AOA ESM tracker.

The study to date has not examined the report-to-track correlation process (e.g., correlation was assumed in the simulation). Association algorithms of ESM strobes and radar tracks are being developed. Utilization of ID information in the correlation process is being implemented and analyzed.