The Problem of Kill Assessment: A Challenge for Radar Tracking Systems

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Abstract—In this overview, both current and future problems of kill assessment are discussed from a surface navy perspective. The basic terminology of kill assessment is discussed in the introduction, which provides the pedestrian background to the common vocabulary. Some of the underlying sources of potential kill assessment information and aspects of current decision taking methodology is discussed in the section on endo-atmospheric kill assessment. In the third section, the challenge of exo-atmospheric kill assessment is addressed and a discussion of how to deal with the dearth of data by a data collection experiment is detailed.

Keywords—Track Filtering, Ballistic Estimators, Kill Assessment.

I. INTRODUCTION

The problem of determining if an opponent has been disabled or destroyed by engagement with a weapon has been with us almost since there has been conflicts among humans. As weapon engagements have moved over the horizon (beyond the eyes of the shooter), the situation has increased in complexity. After the shooter has engaged a threat that is observed with a sensor system (tracking), the shooter needs to know the outcome of the engagement to determine whether or not to reengage the threat. Within the military parlance, this is termed the kill assessment problem. A typical before and after picture of an engagement that illustrates the surface navy perspective is shown in Figure 1. It is the surface navy viewpoint of kill assessment that is the perspective discussed here.

The driver that makes precise and timely kill evaluation important to the surface navy is twofold: reaction time (both anti-air warfare (AAW) and theater ballistic missile defense (TBM)) and minimization of unnecessary weapon usage. The shorter the kill evaluation reaction time, the more likely a successful second opportunity weapons assignment and re-engagement can occur. A precise and timely kill evaluation drives second chance reaction time. If the kill evaluation is not precise, one has the problem of repeatedly expending ordnance against an object(s) that is no longer a threat, and waste resources.

The kill mechanisms can be divided into two classes: a hard-kill mechanism or a soft-kill mechanism depending on which type of weapon system is applied to the target. A hard kill mechanism uses a kinetic energy weapon, such as a gun, missile warhead fragments, or bullet, to damage a threat sufficiently so it does not reach its target. A soft kill weapon uses deceptive weapons, such as electronic counter measures (ECM) or chaff rockets to blind the threat’s sensor(s) in an attempt to draw the threat off its target so that the threat does not successfully attack the ship’s defended region. This article concentrates on the hard-kill mechanism. A discussion of soft kill weapons can be found elsewhere (see [10]). Three aspects of the kill evaluation decision are:

1. artificial intelligence/algorithms used in an hypothesis test,
2. weapon system design in terms of its planned damage mechanism,
3. observables available from the sensor system that are used as input into a hypothesis.

The algorithm designer must be cognizant of the fact that kill evaluation is a hypothesis test to be performed after the engagement of the threat. The hypothesis being tested is: Determine if a threat is still a danger to the shooter or a defended region after engagement. Assuming either a hypotheses of kill or no-kill, there are four possible outcomes of a decision process:

1. target wasn’t killed: it was assessed a no-kill,
2. target wasn’t killed; it was assessed a kill,
3. target was killed; it was assessed a kill,
4. target was killed; it was assessed a no-kill.

There are two specific types of hypotheses that one can propose from these four outcomes. The zero hypothesis ($H_0$): is the target wasn’t killed. The first hypothesis ($H_1$): is the target was killed. Each hypothesis has an error associated with it. A type zero error $E_0$ is $H_0$ is true when it is false (the target was judged a kill when in fact it was not killed). A type one error $E_1$ is that $H_1$ is true when it is in fact false (the target was judged a no-kill when in fact it was killed). During the engagement of a single target, an $E_0$ error is more serious since the incorrect determination significantly reduces the chance for a re-engagement. During a medium to high density raid, multiple $E_1$ errors deplete available resources. Thus for the immediate situation (time during one engagement) $E_0$ errors are more important, but in the long term (time for multiple raids) $E_1$ errors are equally important. Some hard kill weapons have been designed to maximize the likelihood of a kill which minimizes $E_0$ errors, while ignoring what effect of this might have on $E_1$ errors. If weapons systems are designed in this manner, improving kill determination techniques become more important.

A sensor system that is used for tracking threats over the horizon typically is not optimized for estimating one particular state variable (position, velocity, angle, range, etc.) Thus, a tracking sensor system is less precise tool for providing the data useful in forming the kill decision than a sensor system optimized for making a kill assessment alone.

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Thus the kill decision is not optimized. Recognizing this fact has lead weapon designers to make a trade-off between the damage mechanism incorporated in the weapon design. The hard kill damage mechanisms can be partitioned into a trade-off between designing the sensor so that it can recognize that the weapon has destroyed the threat, a so-called recognizable kill criteria and actually destroying the threat but not being able to recognize it immediately from sensor data, the so-called mission kill criteria ([11]).

Decision takers have evaluated the consequences of choosing between mission and recognizable kills by choosing to design weapons whose kill mechanism produces a mission kill with a higher probability of success rather than a kill mechanism that produces a recognizable kill with a lower probability of success. Ultimately any new weapon design can choose between this criteria of recognizable versus mission kill. The potential payoffs for kill evaluation techniques that quickly recognize catastrophic kill and classes of non-catastrophic kills is particularly crucial for close range engagements. When a very rapid kill assessment is possible, second shot opportunities become available, where previously they did not exist. In general, a better kill assessment allows better allocation of sensor resources which makes it possible to engage more targets within a given period of time.

In this paper, the discussion of the kill assessment problem is divided into two parts, endo-atmospheric kill assessment and exo-atmospheric kill assessment. When there is significant amount of atmosphere present, damage to a threat changes its smooth aerodynamic characteristics so it has a tendency to exhibit ballistic slowdown. This can be observed after intercept by estimating the acceleration characteristics or by a change in dynamic characteristics (AAW kill evaluation). A similar situation occurs when a TBM is reentering the atmosphere which acts as a filter to strip away the debris-like objects, while aerodynamic objects penetrate quickly into the lower atmosphere. There is no such stripping mechanism to aid in determining if the debris are due to a missile intercept or the natural junk that accompanies warheads in the exo-atmospheric. Also, there is no database of experience within the surface navy community to help in the design of kill assessment algorithms in the exo-atmosphere. We focus on a planned experiment to gather some data that would allow us to build a database of experience to enable us to construct exo-atmospheric kill evaluation algorithms.

II. ENDO-ATMOSPHERIC KILL EVALUATION

The objective of any kill assessment algorithm(s) is to maximize the chance of recognizing a kill from the sensor data one has available. The data is analyzed using techniques that attempt to uniquely characterize target dynamics and detect post-intercept changes in the threat's underlying dynamics. The great advantage of the atmosphere is that it aids in this process of trying to recognize changes in the state dynamics. A change in state dynamics provides an indication of damage or a recognizable kill. (See Figure 1) Alternatively, instead of dynamic change, if a sensor has established some type of pattern associated with the threat (IR signature, radio frequency transmitter noise characteristics, blackbody emissions), then some abrupt change to the pattern can be recognized as a non-dynamics indicator of damage. The usage of different sources of dissimilar data and its importance must be factored into an "intelligent decision maker" that weights the relevance of each source of data as it is combined to form an overall decision of kill or no-kill.

A combination of non-dynamic indicators can be used in concert with dynamic indicators as the source of kill evaluation information. Kill evaluation, is by nature, a decision based on incomplete information. (We can almost never be certain that a decision is correct about based on information derived from sensors within an allotted kill assessment time, only that it is highly likely.) Thus, one tries to build a decision system based on several different sensor algorithms that provide inputs to the decision process based upon several different indications of changes that have occupied to the threat. The information from the individual procedures are then combined to form a corporate final decision of kill or no-kill. The more variety in the indicators, the better the decision usually can be. The decision process can implemented by a simple table driven process or be implemented as a rule based intelligent decision maker. The details of the implementation of the decision process, of course, depend on the computational resources available both from the signal processing of data as well as the resources necessary to build an "intelligent" decision maker.

A. UNDERLYING DYNAMICS

The physical process of damaging a threat produces an observable effect by changing the motion characteristics of the threat. Thus, any form of acceleration may be indicative of damage to the threat or it could also be indicative of a maneuver. Since acceleration can be written as where the tangent vector is $\mathbf{T} = \frac{\mathbf{v}}{\mathbf{v}}$ and the normal vector $\mathbf{N}$, is along $\frac{\mathbf{v}}{\mathbf{dt}}$ perpendicular to $\mathbf{T}$,

$$a = \frac{\mathbf{d^2s}}{\mathbf{dt^2}} + \kappa \frac{\mathbf{ds}}{\mathbf{dt}} \mathbf{N}.$$  (1)

This allows us to deconstruct the acceleration into two distinct components: that which measures a decrease or increase in speed $\frac{\mathbf{d^2s}}{\mathbf{dt^2}}$ and that which is a measure of velocity change due to change in direction $\kappa \frac{\mathbf{ds}}{\mathbf{dt}} \mathbf{N}$. The second derivatives (accelerations) are expressed in terms of changes in speed or differences in individual components. The magnitude of the acceleration $|a|$ is given by (continuous time replaced by time step $n$)

$$|a| = \sqrt{\frac{(v_x(n)-v_x(n-1))^2}{(\Delta t)^2} + \frac{(v_y(n)-v_y(n-1))^2}{(\Delta t)^2} + \frac{(v_z(n)-v_z(n-1))^2}{(\Delta t)^2}}.$$ (2)
Recall \( \frac{dv}{dt} = |v| \), so \( \frac{d^2s}{dt^2} \) in its discrete form becomes 
\[
\frac{d^2s}{dt^2} = \frac{\sqrt{v^2(n) + v^2(n) - v^2(n) - v^2(n-1) - v^2(n-1)}}{(\Delta t)}. \tag{3}
\]
The magnitude of \( a \) is 
\[
|a|^2 = \left( \frac{d^2s}{dt^2} \right)^2 + \kappa \left[ \frac{ds}{dt} \right]^2. \tag{4}
\]
So the change in direction is given by 
\[
\sqrt{|a|^2 - \left( \frac{d^2s}{dt^2} \right)^2} = \kappa \left[ \frac{ds}{dt} \right], \tag{5}
\]
which is the magnitude of the maneuver term.

All bodies that move through the atmosphere are subject to aerodynamic forces which are a function of the velocity. An analysis of the solution of the equations of motion when atmospheric forces are considered in the differential equations indicates that the factor that dominates the effect of acceleration is the ballistic coefficient of the object ([2], [4], [9]) which effects the objects drag in the atmosphere. For both endo-atmospheric AAW and TBM applications, changes in the ballistic coefficient are indicative of target damage so great that the threat's trajectory is no longer of concern. Estimators of the ballistic coefficient can be applied to both air and endo-atmospheric TBM threats as indicators of a potential kill so they should be included in an overall kill evaluation algorithm. Note one has to separate estimates of the ballistic coefficient from estimates of the acceleration. For a tracking radar, the most important indicator of a destroyed threat is the loss of the track after intercept due to the radar no longer being able to detect the threat. Most of the variables mentioned above are not directly measurable with tracking radars; they measure position while a few measure both position and velocity. Knowledge of how estimates of the components of the position, velocity, and acceleration are crucial. Thus, one has to consider a number of important issues associated with track filtering as discussed in ([1],[9]) which are not discussed further, for brevity.

The method is general enough to work for any dispersive system of the type we are discussing. An estimator can be derived based on the following observation: Any dispersive system that can be written as 
\[
\frac{d}{dt}(T + V) = \frac{d}{dt} E = F' \tag{6}
\]
where \( F' \) is the portion not derivable from a potential, \( T + V \) is kinetic plus potential energy or the total conservative energy \( E_0 \), and \( F \) is the portion of the force not derivable from a potential or the power delivered by an effective force \( F' \).

For example, the normalized \( E_0 \) is 
\[
E_0 = \frac{1}{2} t^2 + g z \tag{7}
\]

There are several possibilities for the effective force, depending on the circumstances. An estimator can be determined independent of the details of what \( F' \) functional form provided it is assumed that \( F'(v) = \kappa f(v) \). To derive an estimator, the derivatives and the variables are made discrete, \( \Delta t = (\delta t - \delta t - 1) \) so this becomes after summing over \( i \) gives 
\[
E_n - E_0 = \sum_{i=1}^{n} k_i \rho_i v_i f(v_i)(t_i - t_{i-1}). \tag{8}
\]
If one defines \( D \) as the negative of the right hand side of this equation and recognizes that the variables are measurements, the energy loss estimator \( LE \) is formed 
\[
LE = D + \dot{E} - \dot{E}_0 \tag{9}
\]
which can be used as one's test statistic for a hypothesis test. To deal with accelerations in the \( z \)-component of the position is a more complicated problem. There are other alternatives to the energy estimator besides those already mentioned.

B. Examples of non-dynamic kill information

One of the possible sources for non-dynamic indicators of damage to a threat are changes in the electromagnetic emissions. A correlation of changes of electromagnetic emissions within the time of intercept of the missile is an indicator of a potential kill, even if it is not a recognizable kill. In the radio frequency spectrum, some types of missiles have active seekers which are used to locate the shooter. The emissions of these seekers can be monitored with passive sensing equipment and if the seeker tracks can be correlated with the shooter's radar track, then there is another indicator of a potential mission kill. Similar things can be said about threats that are jamming the shooter radar that shut down at the same time that a missile intercept occurs. Another indicator would change in the pulse-repetition-frequency (PRF), which is a characteristic of some of the electronic equipment aboard the threat, has change significantly from the pre-established pattern that the passive sensor has established. In the near optical or optical regime, the emission characteristics of the body changing can be an indicator of a change. For example, a jet or rocket engine has emission characteristics that are exhibited by a certain spectral curve with characteristic hot spots. Significant damage can shut the engine off which would be indicated by a rapid change in the color (spectral content) characteristics of the threat. Similarly, if one can produce an optical image of the threat, damage may be visible in post-intercept changes to the image. The problem of kill assessment and target identification are related subjects. For kill assessment, patterns extracted from a sensor signal before a missile intercepts a target would be compared to those extracted after the missile intercept to categorize target damage. Similarly, target identification requires extracting a pattern from the sensor signal and associating it with a pattern from a specific target or a target class.
Thus, all of the problems associated with trying to recognize these changes, can pose a significant artificial intelligence recognition problem when these pattern recognition techniques are automated. Some radars that are used for tracking can also be used to determine other characteristics of the threat besides nominal tracking information. For example, an estimate of the radar cross section (RCS) or the amplitude count can be estimated using conventional tracking waveforms as a consequence of the way they operate. Post-intercept changes above the normal statistical variation can be indicative of threat breakup. With special radar waveforms, one essentially form an “image” of the threat, that can be used to estimate the size and shape of a threat. If the image after intercept shows size changes, then this a fairly strong indicator of a kill. There is a number of other electromagnetic sources of information, polarization matrix for example, that have been used to aid in target identification ([12]). Any of these sources of information can also aid in kill evaluation since identification and kill assessment are related problems. The most important source of information other than that obtained from a tracking radar is Doppler information which we discuss in the next section.

C. Doppler Information

At one time, a large number continuous wave (CW) radars operating at X-band frequencies, were used aboard many destroyers. Now, most of these ship have been decommissioned, so only a few ships were left with this ability. The old systems transformed the signal to an audible range so a fire control operator could “listen” to the intercept (Figure 2). For experienced operators, the audio signal provided the necessary data to determine quickly whether the intercept was a kill. Most modern cruisers and destroyers are commonly equipped to use illuminators (but they don’t have the capability to receive the signal they broadcast) to illuminate a target during the terminal phase of intercept. This provides the missile seeker the signal it uses to home on the target. At present, most naval weapons control systems make little use of the Doppler reflected signal for kill assessment or target identification purposes even though the Doppler spectrum is rich in information about the target.

According to theory ([5],[6],[7],[8]), the received signal contains frequency information due to the non-uniform motion of the target, hence kill evaluation data. Consequently, it is possible to use the Doppler spectrum of the radar signal to characterize the target. Assuming that the necessary signal processing techniques to extract these patterns from the return Doppler can be developed. The one dimensional patterns can be formed from the Doppler spectrum obtained from a continuous wave (CW) radar after taking the Fourier transform of the sampled (discrete) data it and displaying it in a chart as shown in Figure 2. An ideal spectrum is shown in Figure 3. The derived information could then be used for both kill assessment and target identification. An example of what the spectrum looks like for an accelerating target is shown in Figure 4. The presence of a spectrum like this shown, or a spectrum with a large number of accelerating objects is indicative of a kill. The type of data that the techniques that have been developed are applicable to CW radars or high pulse repetition frequency (PRF) radars.

III. EXO-ATMOSPHERIC KILL EVALUATION

There is not a great deal of experience intercepting threats outside of the atmosphere. The problem of exo-atmospheric discrimination between the threat vehicle and the accompanying debris, as well as other sources of false alarms (rocket fuel tanks for example) remains a difficult problem to be solved. System designers would like to avoid a solution that requires the introduction of a new sensor if possible. Ideally, modification to existing hardware or algorithms would be preferred. The endo-atmospheric problem has the solution of letting the atmosphere sort out the high ballistic coefficient objects from the low ballistic coefficient objects. (These have a tendency to slow down, hence are not threats.) This solution, while appealing to some, remains unsatisfactory when reaction time is crucial to the solution. This forces one to find a solution that would enable one to discriminate in the exo-atmosphere using ground based sensors.

The problem of exo-atmospheric kill assessment has many difficulties not associated with endo-atmospheric kill assessment. A typical geometry is shown in Figure 5. Rather than a design for maximizing mission kill as has been done for many systems, this does not appear to be a viable option with conventional warheads because of the relative speed between threat and kill vehicle. Thus the option being explored is to build a so called “hit-to-kill” vehicle. Besides the technical difficulties of arranging a successful “hit”, the problem remains if the hit actually destroyed the threat. Most of the obvious properties associated with physical damage mechanisms become observable quickly within the atmosphere; drag, for example, non-aerodynamic objects slow down quickly, so the effects can be observed quickly in the atmosphere. This advantage is not present in the exo-atmosphere, so one is faced with the quandary of deciding what physical mechanism is observable with a sensor indicates significant damage or a kill. The Doppler data from previous experience in the endo-atmosphere appears to be the best source of potential information that is indicative of a kill. Since there no exo-data available to test ideas, a reasonable first step to solving this problem was thought to be gather some Doppler data during intercept tests of the exo-atmospheric interceptor. NSWCDD personnel are involved in a data collection experiment to gather such Doppler data which we now describe.

A. RTDS System Overview

The RTDS is a Non-Cooperative Target Recognition (NCTR) system which is a subsystem of SATRIS II designed to interface with the other components of SATRIS II, two R-2919U/UPX-34A Radar Receivers, and two MK 99 Mod 2 Fire Control Systems (FCS). The objective of the
RTDS is to identify Anti-Air Warfare (AAW) tracks by performing Radar Signal Modulation (RSM) processing of the spectral components of the radar returns provided by the FCS radars. The track description is displayed locally in the RTDS and declared externally to FCS. In addition, the local display unit of the RTDS provides a means to perform testing and monitoring of the system status. The predecessor to SARTIS is the Ship’s Advanced Target Identification system (SARTIS) which is currently in use onboard the AEGIS Cruiser Ships. The upgrades to this system include the replacement of the current R2919/U radar receivers with R-2919/U/UPX-34A radar receivers and replacement of the current processor boards of the RTDS with COTS processor boards. The COTS approach was taken to maximize the flexibility for future enhancements to the RTDS. (The RTDS enhancement is being developed by Condor Systems for NAVAIR for placement on the AEGIS Cruisers.)

B. Collection of Data to Assess TBM/Exo-Interceptor Lethality

There have been some interesting proposals that involve new sensors or non-traditional observables that do not yet have much empirical basis. Discussion of these potentials lie outside of discussion in the open literature. Continuous Wave (CW) radars, such as the MK-99 FCS, have proven useful in collecting Doppler Data. This endo-atmospheric data has proven a valuable information about missile intercepts so exo-atmospheric data is thought to be useful as well. Past experience and the potential for collecting Ballistic Missile intercept data is the rationale for the proposed MK-99 Doppler Data Collection Experiment. A study conducted in FY97 concluded that Theater Ballistic Missile (TBM) Doppler data could be collected by the AEGIS MK-99 Fire Control System (FCS) during TBM intercepts. Based upon this conclusion, NSWC DD has been tasked to perform a Data Collection experiment (shown in Figure 6) as part of Navy Theater Wide (NTW) Flight Test Round-2 (FTR-2) tests. This test will be performed as part of FTR-2. It will be performed to determine the suitability of using the MK-99 system with a receiver to collect Doppler data during a TBM engagement and the potential of using that data to determine intercept lethality. The data will be collected during a SM-3 TBM encounter to determine if sufficient information is in the data to estimate intercept lethality. This will be the first Doppler data collection on an exo-atmospheric TBM intercept; therefore, modeling would be too speculative although this equipment or similar equipment has been previously used for Doppler data collection on aircraft and Standard Missiles.

The data from this test will be used to assess the suitability of using Doppler data for determining lethality of exo-atmospheric intercepts. This test will be performed during a pre-planned exercise and the objective is to assess the potential of using Doppler data collected during an intercept to assess intercept lethality. Since no Doppler exo-atmospheric intercept data has been collected prior to this experiment, this experiment is necessary to start developing the database to evaluate the stated potential of Doppler intercept data in determining intercept lethality.

To develop methods of performing kill assessment on exo-atmospheric engagements, a database of the characteristics of these type intercepts must be developed. An objective of these experiments is to start developing that database. Results will be start to be obtained in 2003.

IV. Conclusions

In this paper, we have discussed the basics of the kill evaluation problem. We have noted that there are three aspects to the problem:

- the characteristics of the threat that would be indicative of damage from the available sensor observables
- robust algorithms to estimate the observables characteristics obtained from the sensor sources
- an artificial intelligence algorithm to use the estimates derived from sensor data to reach a final decision of whether or not the target has been killed.

The problems associated with the endo-atmospheric kill evaluation involve fine tuning existing algorithms, refining the decision process algorithms, and integrating more sensors into the decision process. The problems with exo-atmospheric kill evaluation remain largely unsolved and require the gathering of sensor data to better understand what observables are characteristic of a kill and how they can be estimated. The problem of kill evaluation remains a challenge to the estimation community for the foreseeable future.

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REFERENCES

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.