# Tomahawk Deconfliction: An Exercise in System Engineering

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Improvements to the navigational and timing accuracy of the Tomahawk Block III missile resulted in the need to deconflict missiles, that is, to prevent missile-to-missile interference during flight. The Applied Physics Laboratory identified the potential risks resulting from the missile's increased accuracy, quantified the resulting probability of collision, and identified a deconfliction solution. This effort required a broad system knowledge of Tomahawk and its supporting systems. Because so many different factors influence deconfliction—from Global Positioning System accuracy to overall engine performance—the solution must continue to be evaluated as the weapon system evolves. The Laboratory continues to educate users about deconfliction, to monitor its effective use, and to analyze the potential effects on deconfliction of weapon system developments. This ongoing system engineering effort assures the continued effectiveness of the Tomahawk deconfliction solution.
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## INTRODUCTION

The Tomahawk Block III missile was first used operationally in Bosnia on 10 September 1995. The onboard software automatically determined a small route offset for each missile. These offsets *deconflicted* the missiles, preventing missile-to-missile interference during flight. Without automatic deconfliction, some of these missiles probably would not have reached their targets. As Technical Direction Agent for Tomahawk, APL had identified the need for missile deconfliction, quantified the risks, and directed implementation of a solution. The analysis and solution were an exercise in total system engineering that required an understanding of all Tomahawk system components, from mission planning to the weapon control system to the missile itself. As the Tomahawk system evolves, APL continues to evaluate the deconfliction solution against new developments to assure that it continues to protect against missile interference.

The question of missile deconfliction was raised early in the development of the Tomahawk missile. Before deployment of the Block III missile, the standard answer was the "Big Sky-Little Missile" theory: "It is a very big sky and a very little missile. The chance of two missiles being in the same place at the same time is too small to worry about." This theory was not based on formal analysis, but rather on a sense that the navigational and timing uncertainties of the missile made collision unlikely. Relatively few Tomahawks were deployed in the Fleet, and use of large numbers of Tomahawks in a single strike was not considered a likely scenario. The limited numbers and the large uncertainties made missile interference extremely unlikely.

As the Tomahawk system matured, the number of missiles in the Fleet rose. Tactical use of the Tomahawk during Desert Storm in 1991 showed large numbers of Tomahawks employed on relatively few routes. Subsequently, the Block III missile greatly reduced the navigation and timing uncertainties with Global Positioning System (GPS) navigation and time-on-target (TOT) control (which adjusts speed during flight so that the missile arrives at the target at a specified time). Improved accuracy and increased missile numbers raised concerns over potential missile-to-missile interference. At APL, we set out to determine when missiles might interfere with one another, to quantify the probability of interference, and to develop a solution for deconflicting the missiles.

## DEVELOPMENT OF THE DECONFLICTION SOLUTION

We began characterization of the interference potential by breaking the problem down into specific instances where missile interference could be a concern. As the list of potential areas of concern grew, it became clear that they were all related. Whenever multiple missiles are in the same area at approximately the same time, there is a potential for interference. Missions were examined from launch to impact. Risk of interference at launch was assessed as low, but terminal fratricide (damage to a missile from the blast effects of another missile) and en route interference (a missile-to-missile encounter during flight) required additional analysis. APL conducted separate analyses to quantify the probability of interference for each of these cases. When analysis indicated the need for missile deconfliction, APL proposed a solution, which was quickly implemented by McDonnell Douglas and delivered to the Fleet. As the Tomahawk Weapons System continues to evolve, APL continues to monitor the system engineering impacts on the deconfliction solution's effectiveness, including assessment of strikes into Iraq and Bosnia.

### Terminal Fratricide Analysis

Initially, concern over missile interference focused on terminal fratricide caused by target debris, missile body debris, blast waves, or warhead fragments. Earlier studies[1] showed that blast wave effects and target debris have limited range, resulting in little or no opportunity to affect a trailing missile. Similarly, missile body debris is range-limited compared with the titanium warhead fragments. Because of their range, velocity, and ability to penetrate walls, these warhead fragments pose the most serious threat to a succeeding missile.

Two basic considerations arise in the analysis of warhead fragment effects: How likely are the fragments to hit a trailing missile, and what is the resulting damage if a fragment-missile collision occurs? The APL analysis, described in the following paragraphs, showed that the probability of a missile being hit by warhead fragments is extremely small, even for small differences in TOT. Since these probabilities are so small, potential missile damage due to fragment impact was not addressed in detail.

A closed-form expression for the probability of a fragment hitting a missile cannot be formed because of the nonlinear, nonuniform nature of the problem. Monte Carlo techniques, however, provide a method to estimate the probability of hit based on a particular set of scenarios. Scenario selection used a worst-case analysis based on the warhead fragmentation data from arena tests at the Naval Surface Warfare Center-China Lake. These tests indicated that the fragmentation pattern for a Tomahawk Block III warhead is highly directional rather than uniform. Figure 1 shows the four worst-case scenarios used for analysis: (1) identical dive, (2) parallel dive, (3) opposite dive, and (4) opposite airburst. Each scenario has the trailing missile fly through the densest debris clouds. These scenarios drive the warhead/missile simulation developed by APL.

The warhead/missile simulation evaluates the probability of hit by modeling a fixed number of fragment trajectories from a single warhead detonation as a function of time. Random initial velocities and masses are selected for each fragment; then, depending upon the scenario, the trailing missile's position and the positions of all fragments are computed. These positions are compared over time to determine whether a hit occurs. To estimate the overall probability of hit, many different detonations were simulated. Each simulated detonation differed because of the randomness of each fragment's initial velocity and mass. An estimate of the probability of hit was calculated as the ratio of the number of simulated detonations in which the missile was hit by at least one fragment to the total number of detonations.

The results of repeated Monte Carlo simulations for each of the four scenarios are shown in Fig. 2, where the probability that a missile is hit by one or more fragments is plotted versus missile separation time. The probability of hit is extremely small, even for modest TOT differences, because the fragments are widely

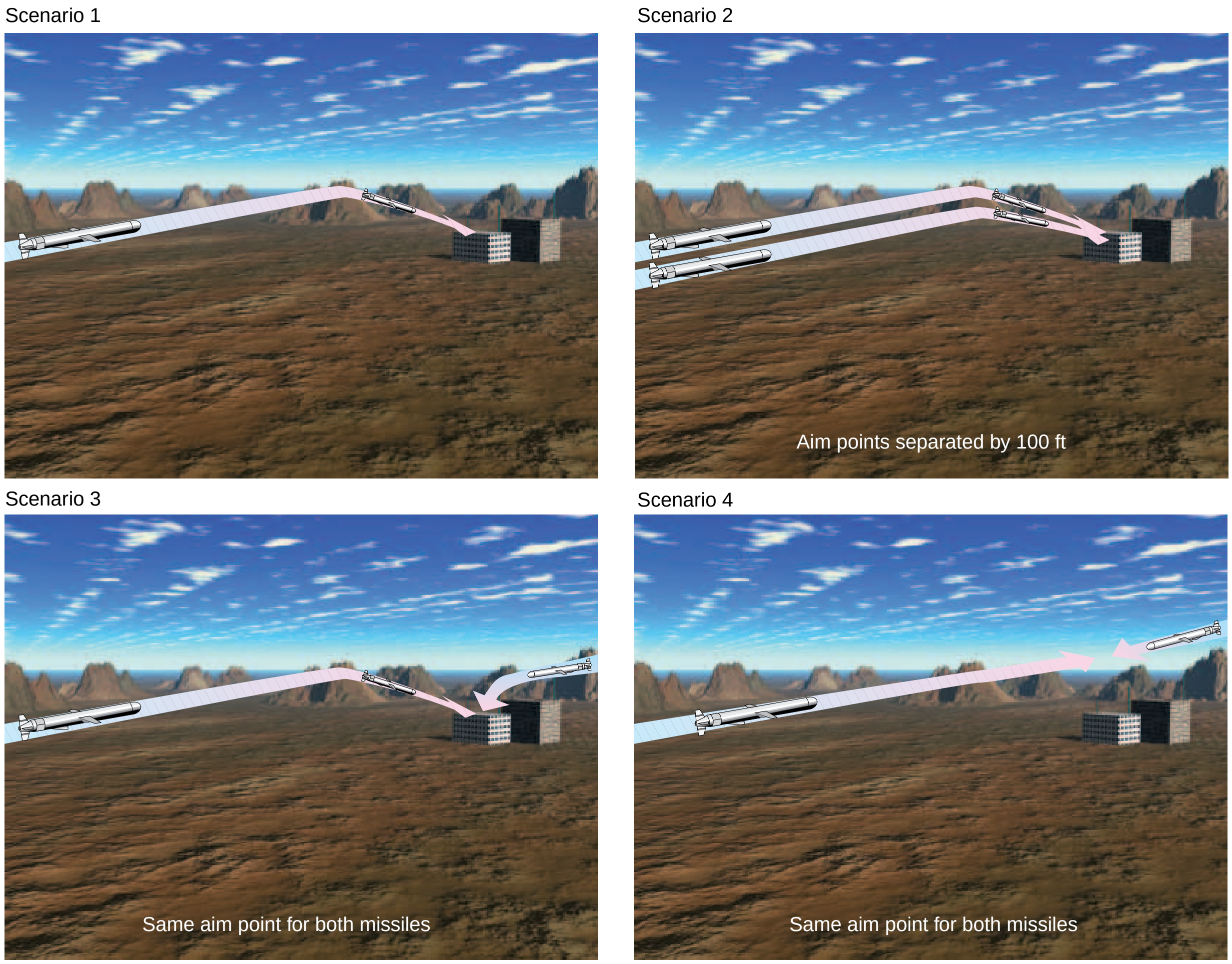


**Figure 1.** The four worst-case operational scenarios used for analysis of the potential for terminal fratricide (i.e., damage to a missile from the blast effects of another missile). Scenario 1, identical dive; scenario 2, parallel dive; scenario 3, opposite dive; and scenario 4, opposite airburst.

dispersed very shortly after detonation and the missile is relatively small. The opposite dive scenario (scenario 3) shows the highest probabilities because in this scenario the missile passes through the densest fragment cloud. The probabilities for parallel dive (scenario 2) are higher than those for identical dive (scenario 1), even though the trailing missile is further from the point of detonation, because a trailing missile in a parallel dive has a larger vulnerable surface area at all times. Opposite airburst (scenario 4) did not prove to be particularly vulnerable. For all scenarios, the probability of hit is less than 0.005 for missile separation times greater than 3 s.

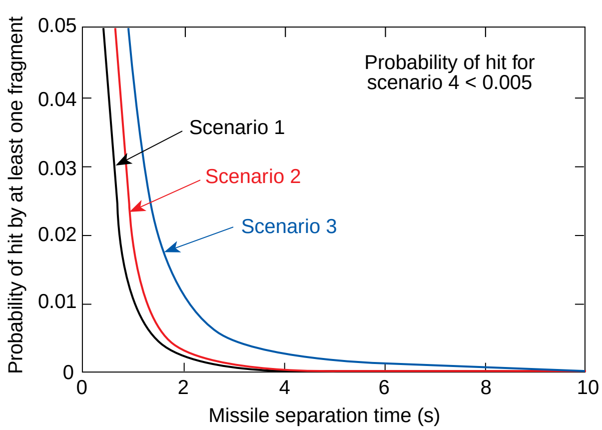


**Figure 2.** Results of Monte Carlo simulations for the terminal fratricide scenarios of Fig. 1, showing the probability of a hit by at least one fragment.

Although the analysis did not specifically address the effect of a hit on a trailing missile, the method just described can be slightly modified to estimate the probability of the trailing missile being hit by one or more heavy fragments. These are the fragments most likely to damage or destroy the missile. To estimate the probability of hit by heavy fragments, the ratio of the total number of simulations in which the missile was hit by at least one heavy fragment to the total number of simulated detonations was computed. Any fragment weighing 0.5 lb or more is considered heavy. For all scenarios, the probability of hit by a heavy fragment is less than 0.005 for missile separation times greater than about 1.2 s.

Overall, the probability of a missile being hit by debris from a previous missile impact is small. The conclusions of this analysis indicate that terminal fratricide is not a concern for TOT separations greater than 3 s, a relatively small separation in comparison with variations in firing time and missile speed.

## En Route Interference Analysis

Characterization of potential missile interference suggested that any time missiles were supposed to be in the same place at approximately the same time there was the potential for a collision. Since many missiles can share the same basic route to a single target or a set of targets, an analysis of the probability of collision along the flight path was necessary. The basic probability of en route collision was calculated in two parts: What is the probability that two missiles will pass, and what is the probability that two passing missiles will collide?

The probability that missiles will pass depends on the missiles' abilities to control their speeds. Each missile has a commanded speed; however, the actual speed flown by the missiles may vary. Two missiles will pass if the difference between their speeds is large enough. For missiles without TOT control, this speed difference can be represented by a Gaussian distribution with a mean of 0 and a standard deviation of $\sqrt{2}\sigma_{\text{speed}}$, where $\sigma_{\text{speed}}$ is the standard deviation for an individual missile's speed. This standard deviation is driven by variations in the missile's air data system. Using this distribution, the probability of passing is the probability that the difference in missile speed will exceed some critical value. The critical value is determined by the initial missile separation and the nominal missile speed. The addition of TOT control to a mission changes the probability of passing. In effect, TOT control calibrates the missile speed at each waypoint, or turning point, eliminating the effects of the air data system variations. The probability of passing is significantly lower for missiles with unique TOT assignments that arrive on the common path in order; however, missiles that arrive out of order have a probability of passing that is close to 1 because the system will attempt to force a pass.

The probability of collision while passing depends on the navigational accuracy of the missiles. If two missiles are flying along a common route and they pass, the difference in their relative accuracy determines whether they will collide. These differences arise through a combination of guidance and control variations, GPS errors, and altimeter performance issues.[2,3] As was the case for the speed distribution, these differences in missile position can be expressed as Gaussian distributions. A collision will occur if the differences between the missile locations in both the cross-track and altitude dimensions are small enough. The critical values for cross-track and altitude collisions must account for missile size, potential aerodynamic interference, and noninstantaneous passing. These factors define the interference zones shown in Fig. 3; note that actual physical contact is not necessary for a collision to occur.

Combining these results for the probability of passing and the probability of collision while passing produces a quantitative closed-form expression for the probability of two missiles without TOT control colliding (see Table 1). As demonstrated in every operational use of Tomahawk, more than two missiles may share a common route. APL built upon the two-missile equation to allow for analysis of an *N*-missile scenario—some number *N* of missiles flying a common route segment with an initial time separation of $\tau$ seconds between arrivals at the common route. The *N*-missile probability of collision refers to the probability of at least one collision occurring.

In developing the *N*-missile equation, the key observations are that every possible pair of missiles has some probability of collision, and the probability of at least one collision is simply 1 minus the probability that none of the missiles collide. Let $p(\tau)$ represent the two-missile probability of collision for missiles initially spaced $\tau$ seconds apart. For the three-missile case, no collision will occur if missiles 1 and 2 do not collide

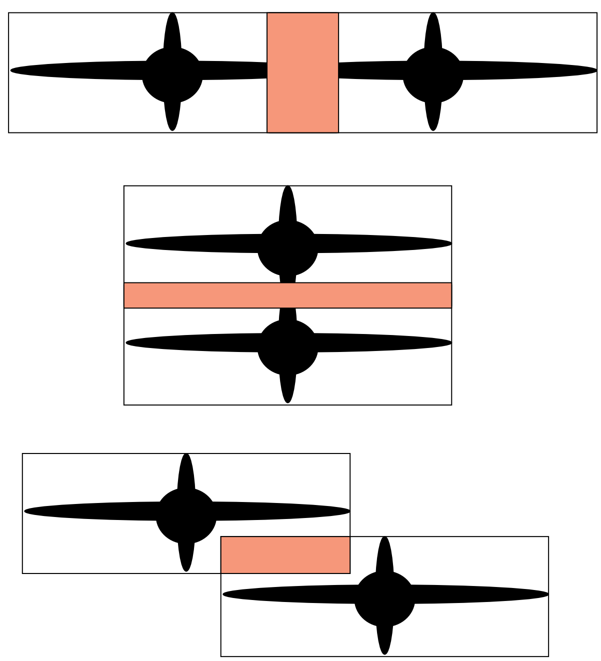

**Figure 3.** Missile collision examples. Missile size, potential aerodynamic interference, and noninstantaneous passing define interference zones; actual physical contact is not necessary for a collision to occur.

**Table 1. Equation for the probability of collision of two missiles without time-on-target control while the missiles are en route to the target.**

| Parameter | Symbol | Equation or definition |
|---|---|---|
| **Two-missile probability of collision** | $P_{\mathrm{C}}$ | $P_{\mathrm{p}} \times P_{\mathrm{CWP}}$ |
| ◆ Probability of passing | $P_{\mathrm{p}}$ | $\int_{\Delta s_r}^{\infty} \frac{\exp\left(-\frac{x^2}{4\sigma_{\mathrm{speed}}{}^2}\right)}{2\sigma_{\mathrm{speed}}\sqrt{\pi}}\,dx$ |
| • Speed standard deviation | $\sigma_{\mathrm{speed}}$ | Standard deviation of a single missile's speed; depends on air data system and engine performance variations |
| • Required speed differential for passing | $\Delta s_{\mathrm{r}}$ | $\frac{s_{\mathrm{c}}^2\tau}{D_{\mathrm{CR}} - s_{\mathrm{c}}\tau}$ |
| – Commanded speed | $s_{\mathrm{c}}$ | Speed the missile is supposed to be flying; set in mission planning |
| – Initial time separation | $\tau$ | Time interval between missile arrivals on the common route; depends on launch rate |
| – Common route distance | $D_{\mathrm{CR}}$ | Distance the missile routes share in common; depends on mission plans |
| ◆ Probability of collision while passing | $P_{\mathrm{CWP}}$ | $P_{\mathrm{AC}} \times P_{\mathrm{CTC}}$ |
| • Probability of altitude collision | $P_{\mathrm{AC}}$ | $\int_{-\Delta h_c}^{\Delta h_c} \frac{\exp\left(-\frac{x^2}{4\sigma_{\mathrm{alt}}{}^2}\right)}{2\sigma_{\mathrm{alt}}\sqrt{\pi}}\,dx$ |
| – Critical height difference | $\Delta h_{\mathrm{c}}$ | Maximum height difference when a missile collision will occur in the altitude dimension; depends on missile physical dimensions and aerodynamic effects |
| – Altitude standard deviation | $\sigma_{\mathrm{alt}}$ | Standard deviation of a single missile's altitude; depends on altimeter variations |
| • Probability of cross-track collision | $P_{\mathrm{CTC}}$ | $\int_{-\Delta x_{\mathrm{c}}}^{\Delta x_{\mathrm{c}}} \frac{\exp\left(-\frac{x^2}{4\sigma_{\mathrm{ct}}{}^2}\right)}{2\sigma_{\mathrm{ct}}\sqrt{\pi}}\,dx$ |
| – Critical cross-track difference | $\Delta x_{\mathrm{c}}$ | Maximum width difference when a missile collision will occur in the cross-track dimension; depends on missile physical dimensions and aerodynamic effects |
| – Cross-track standard deviation | $\sigma_{\mathrm{ct}}$ | Standard deviation of a single missile's cross-track position; depends on GPS and guidance and control errors |

$[1 - p(\tau)]$, if missiles 2 and 3 do not collide $[1 - p(\tau)]$, and if missiles 1 and 3 do not collide $[1 - p(2\tau)]$. This produces the following three-missile probability of at least one collision:

$$1 - \{[1 - p(\tau)][1 - p(\tau)][1 - p(2\tau)]\}\,, \qquad (1)$$

or, using the mathematical approximation for small $p$, $1 - p \cong e^{-p}$, the 3-missile probability of at least one collision can be expressed as

$$1 - e^{-[2p(\tau) + p(2\tau)]}\,. \qquad (2)$$

Adding a fourth missile adds three new pairs of missiles (one pair $\tau$ seconds apart, one pair $2\tau$ seconds apart, and one pair $3\tau$ seconds apart) for a probability of at least one collision of

$$1 - e^{-[3p(\tau) + 2p(2\tau) + p(3\tau)]}\,. \qquad (3)$$

Generalizing this to an $N$-missile equation for the probability of at least one collision among $N$ missiles without TOT control yields

$$P_c(N) = 1 - e^{-\sum_{i=1}^{N-1}(N-i)p(i\tau)}\,. \qquad (4)$$

Once the analytical methodology was in place, we determined the appropriate fixed-input parameters for the Tomahawk missile system. These included navigational accuracy, which is based on relative GPS performance and altimeter specifications, and the speed fluctuations that result from air data system variations. Other parameters, such as length of mission, number of missiles, and initial missile separation, were allowed to vary so we could investigate different scenarios. Figure 4 shows, for a 600-nmi common route and initial missile separations of 10, 30, and 60 s, curves of the probability of collision versus the number of Block III missiles without TOT control. The probability of collision values are omitted due to classification; however, the values are exponential in the number of missiles, and probabilities reached into the double digits. For missiles on common routes flying without TOT control, deconfliction is clearly required.

To examine the deconfliction requirements for missiles using TOT control, we used the same basic equations. The input parameter that changes is the probability of passing, which depends upon the assigned TOT of the missiles. Missiles with very closely spaced TOT assignments could pass each other multiple times en route to the target. As the difference in assigned TOT approaches zero, the probability of collision approaches

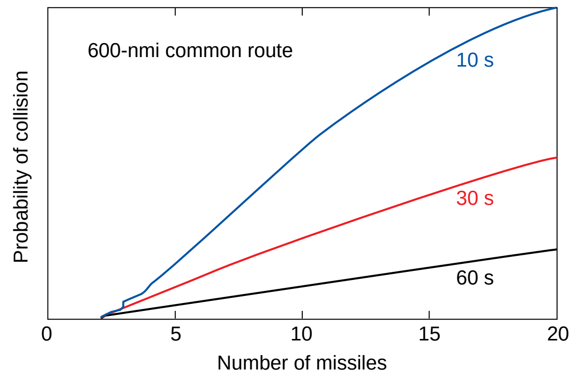


**Figure 4.** The $N$-missile probability of at least one collision. (Tomahawk Block III without time-on-target control). Curves show the probability of at least one collision en route to the target with initial missile separations of 10, 30, and 60 s.

1 for missiles with identical assigned TOT as the length of the common route increases. As the TOT separation increases, the probability of collision rapidly decreases because of TOT speed calibration. An additional twist occurs if missiles with unique TOT assignments arrive on a common route out of sequence (that is, the missile with the later TOT arrives on the common route first). In this case, the probability of passing is 1, since the missile software essentially forces a pass to achieve the assigned TOT. Thus, TOT control presents a more complex probability of collision picture, but the need for deconfliction measures remains clear.

## Deconfliction Solution and Implementation

Our analysis of the probability of collision was initiated shortly before the Block III missile was scheduled to arrive in the Fleet. Terminal fratricide had originally been considered the most likely area of interference; the relatively high probabilities of collision shown by the en route analysis had not been anticipated. After briefing the Tomahawk community on the analysis and achieving a consensus that the potential for en route interference was indeed high, we set out to define a solution that could be provided to the Fleet in time for the arrival of the Tomahawk Block III missiles. Because time was short, we took a two-phase approach, limiting the initial phase to a procedural solution. In the second phase, a wider range of options was considered.

Whenever multiple missiles are trying to be in the same place at the same time, there is a potential for interference. Any deconfliction solution must remove one or more of these elements. How can this be achieved procedurally? The number of missiles in a given strike is driven by tactical considerations—what the required damage to the target area is and how many missiles are necessary to achieve that level of damage. Changing the number of missiles would interfere with achieving the strike objectives. The remaining deconfliction options are to separate the missiles in space by using different routes or to separate the missiles in time by using launch spacing. Missiles on different routes cannot interfere with each other until they reach the target area, and the terminal fratricide analysis shows that the probability of interference in the target area is low. Creating an entirely separate mission for every missile launched, however, is not necessarily an option. Mission planning can be a time-consuming process, especially when a limited number of scenes are available for navigation updates. Separating missiles in time can also procedurally deconflict missiles. We developed a matrix of separation times required to deconflict different numbers of missiles for common routes of various lengths. The temporary procedural guidance issued to the Fleet advised a combination of spatial and temporal separation: it recommended use of multiple routes to reduce the number of missiles per route and use of time separation for those missiles remaining on a common route. TOT control was not addressed by the temporary guidance since it could not be used until after a subsequent weapon system upgrade, when the second-phase deconfliction solution would be in place.

Although the temporary procedural solution provided adequate missile deconfliction, it was tactically undesirable. Large missile separations in the target area can increase vulnerability to threats and make coordination more difficult. Procedural deconfliction also imposed extra responsibilities on the mission planners and the Fleet. Four primary goals were used in developing the second phase of the deconfliction solution:

- Reduce the probability of collision to acceptable levels for missions with and without TOT control.
- Maintain full operational effectiveness.
- Make the solution as transparent as possible for Navy personnel.
- Contain the cost and schedule so that the tactically undesirable temporary guidance could be eliminated.

Various solution options were developed and evaluated against these goals to determine their suitability for deconfliction.

Several proposed solutions did not adequately reduce the probability of collision. Some solutions worked for missiles with TOT control but not for those without it, or vice versa. This category of solution included reducing air data system errors and calculating the ground speed using GPS. Other solutions were eliminated because they limited the operational effectiveness of the system. The need to maintain full operational effectiveness eliminated the large time separations imposed as a part of the procedural solution because of the potential increased vulnerability to threats. Other conceivable but less promising solutions, such as eliminating the use of GPS or decreasing GPS accuracy, were also ruled out because they limited operational effectiveness. Lack of transparency ruled out elimination of all common routes, because this solution would increase the workload of mission planners.

After many solutions were eliminated because they did not satisfy the primary goals, the remaining options centered on inserting a small automatic route offset, thus putting missiles onto slightly different routes to reduce the probability of collision. To deconflict the entire mission, including the segment of the flight over water, these offsets had to be applied either in the weapon control system or in the missile flight software. The decision between these two options centered on cost and schedule. The flight software is distributed with the mission library and downloaded onto the missile just prior to launch. A change to this software would therefore reach all Tomahawk shooters relatively quickly. The weapon control systems are updated much less frequently, and the change is put into the Fleet gradually as ships are upgraded. In addition, updating the weapon control system would require a change to both the surface ship and the submarine weapon control systems, increasing the overall cost. After consideration of all the possible deconfliction options, we determined that the option that best satisfied the goals of deconfliction, operational effectiveness, transparency, and cost/schedule was inserting a small route offset using the missile flight software.

After selection of the general deconfliction solution, many details remained to be worked out. How many offsets should there be, and how far apart should they be spaced to achieve the optimum reduction in the probability of collision? Would these offsets affect the missile probability of clobber (colliding with the ground) or the probability of update (achieving a navigation fix)? When should the offsets be inserted and removed from the flight path? What is the effect of TOT control? How should the missiles be assigned to offsets? APL developed several Monte Carlo simulations to help answer these questions.

Analysis began with assigning offsets to missiles. To consolidate the solution within the flight software and avoid placing new requirements on the operators, offset assignment had to be distributed, with each missile selecting its offset independently. Given a distributed assignment scheme, offset selection could be either random or deterministic. Random assignment offers the advantage of a simple distributed implementation. Distributed deterministic assignment is more difficult to implement, but can provide better performance than a random scheme. Preliminary analysis indicated that a random assignment algorithm would not sufficiently reduce the probability of collision, so efforts focused on developing a deterministic assignment scheme.

Deterministic missile offset assignment is simple in a centralized scheme. Information is available about all of the missiles so they can be assigned unique offsets. In a distributed scheme, information is much more limited. Each missile must independently select an offset without knowing the number of missiles sharing the route. After considering the information available to each missile, the assignment scheme focused on the launch time and launch location. The minimum separation between missile launch times for a single shooter defines a time interval. A set of these time intervals is associated with each missile offset in a repeating pattern. The minimum separation between missiles from the same shooter sharing an offset is equal to the number of intervals multiplied by the time interval. Thus, the launch time deconflicts missiles from a single shooter. When multiple shooters are involved in a strike, the possibility exists for simultaneous missile firings. To prevent these missiles from sharing the same offset, the placement of the initial offset depends upon launch platform location. This randomizes offset selection between different shooters, reducing the probability of two closely spaced missiles sharing an offset. Monte Carlo simulations indicate that this distributed deterministic allocation algorithm can achieve the required reduction in probability of collision.

The probability of collision reduction depends upon the size and number of offsets. To avoid increasing the probability of missile clobber, the overall width of the cross-track corridor is limited by the size of the mission planning analysis corridor. The conservative mission planning analysis corridor analyzes more ground for probability of clobber than is required for GPS accuracy. This additional analyzed terrain is used for cross-track offsets, thereby maintaining the overall probability of clobber. Vertical offsets involve a trade-off between probability of collision and missile survivability. Simulations demonstrated that a relatively small vertical offset can dramatically reduce the probability of collision. The impact on missile survivability is minimal since vertical offsets are small and are removed before the missile reaches the terminal area where heavy defenses are most likely. Only positive vertical offsets are used, resulting in increased altitude that maintains or reduces the probability of clobber.

Once the overall size of the corridor available for offsets is fixed, the number of cross-track and vertical offsets must be determined. A Monte Carlo simulation was developed to analyze the probability of collision for different numbers of offsets based on different scenarios. The scenario definition included setting the number of missiles, number of launch platforms, and platform firing rates. Based on simulation results, a grid of seven cross-track offsets by three vertical offsets was established.

Offset insertion and removal is influenced by the probability of collision and the probability of navigation update. Since GPS accuracy is responsible for the increased probability of collision, the offset is inserted upon GPS acquisition. To avoid reducing the missile's chance of achieving a navigation fix, the offsets are removed before the first Digital Scene Matching Area Correlator (DSMAC) scene is used. For missions without DSMAC, the offsets are removed before the target area is reached.

A final consideration involves the impact of TOT control on deconfliction. TOT control allows a missile to control its speed during flight to arrive at the target at a specified time. If multiple missiles are trying to be in the exact same place at the exact same time, especially for long distances, the probability of collision is high. The en route offsets help to prevent collision during most of the flight; however, the offsets must be removed in the terminal area before the target is reached. If the missiles are aimed at the same point, the only possible method of deconfliction is assigning the missiles a TOT separation. Minimizing the size of the separation is critical to maintaining Tomahawk's tactical flexibility. The minimum required separation is based on TOT control accuracy, potential aerodynamic interactions, engine performance differences, target area considerations, and the possibility of terminal fratricide.

The second-phase deconfliction solution was implemented, tested, and delivered to the Fleet less than a year after the deconfliction analysis was started, and the solution achieved all four primary goals. It met the cost and schedule containment goals, and deconfliction using automatic missile operational flight software enabled very simple guidance (Fig. 5) that minimized the effect on operators and maintained full operational effectiveness. Analysis of the solution reveals that the deconfliction measures installed in the Fleet reduce the probability of collision by an order of magnitude, returning it to the levels of the Tomahawk Block II missile, when the Big Sky-Little Missile theory was adequate. The solution thus reduced collision probabilities to acceptable levels.

## CONTINUED DECONFLICTION EFFORTS

As Technical Direction Agent for Tomahawk, APL's work extends beyond the initial delivery of an analysis, product, or solution. Part of our responsibility is to continue to monitor the evolution of the Tomahawk weapon system to assure that all the pieces continue to work together properly. Because APL is involved with the system at so many different levels, we have a unique perspective on Tomahawk, enabling us to identify

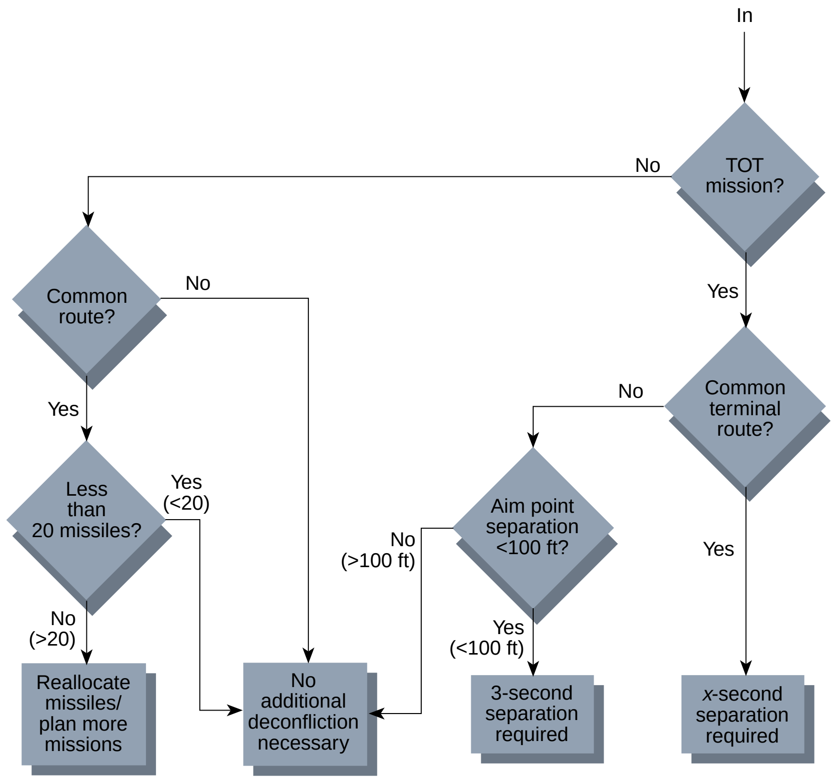


**Figure 5.** Flow diagram of Tomahawk deconfliction guidance (TOT = time-on-target).

changes that have ripple effects throughout the weapon system. Deconfliction is an exercise in this type of total system engineering. The analysis and solution required an understanding of all the components of the system, from mission planning to the weapon control system to the missile itself. Because so many different elements of the system play a role in deconfliction, continuing to follow system developments and to assess their effect on deconfliction are important.

Perhaps the most critical role that APL has played since the delivery of the deconfliction solution is that of educator. Questions on deconfliction originate from multiple sources in both industry and the Navy. We continue to stress the importance of deconfliction and to raise awareness of the guidance and the reasons behind it. We periodically brief personnel at the cruise missile program office, the mission planning activities groups, and the Tomahawk Fleet users group on deconfliction. Documentation is also key to education and training efforts. Deconfliction is included in various Tomahawk naval warfare publications. We provide review and comment on the accuracy and clarity of these documents with respect to deconfliction. This documentation and continued briefing raise Fleet awareness of deconfliction, which is critical to achievement of the lowest possible probability of collision.

In addition to disseminating deconfliction information, APL has continued to monitor deconfliction performance in actual Tomahawk launches. We have verified proper offsets for missiles flown in the operational testing program and have quantified the probability of collision for actual operational strikes to assist in the battle damage assessment. In several cases, quantification of a strike's probability of collision has required us to expand our analytical methodology.

After the January and June 1993 strikes against Zaafaraniyah and the Iraqi Intelligence Center, APL was asked to quantify the probabilities of collision. This required expansion of our methodology because the initial probability of collision analysis was developed for the Tomahawk Block III missile, but both of these strikes used Block II missiles. The navigational accuracy of Block III missiles remains relatively constant, whereas the navigational accuracy of Block II missiles improves throughout the flight. A new Monte Carlo simulation was developed to quantify probabilities of Block II missile collision by assigning missile speeds based on a Gaussian distribution, determining if a pass will occur, and basing the navigational accuracy on where the pass occurs. The specific parameters from the Block II strikes were input into this simulation and the probability of collision calculated as a part of the overall strike evaluation.

APL also calculated the probability of collision after the 1995 Tomahawk strike in Bosnia as part of the battle damage assessment. This strike represented the first operational use of Block III missiles and of TOT control. Previous analysis established that giving missiles with a common terminal route identical TOT assignments resulted in an unacceptable risk of collision; however, the analysis was not detailed enough to numerically quantify these probabilities. To assess the Bosnia strike, APL developed a quantitative approach to TOT control. Essentially, when employing TOT control, missiles can adjust their flight speed throughout the mission to achieve the desired TOT. These adjustments can result in missiles' passing multiple times instead of the single potential pass modeled for nonTOT missions. The probability of collision was computed as a function of the number of passes. The actual number of passes depends upon both the mission and the individual missile's performance. This analytical methodology was combined with data from the launch ship's tapes to compute a probability of collision for the strike in Bosnia. Analysis indicated that the automatic offset algorithm assigned all missiles to unique offsets during the en route portion of the mission.

In addition to monitoring the effective implementation of the deconfliction solution in the current system, APL also evaluates the implications of potential future developments in the Tomahawk missile system. One improvement being considered is use of GPS after the missile's final DSMAC navigation update. Post-DSMAC use of GPS allows missions to be planned with longer distances between the final DSMAC scene and the target by dramatically reducing the effects of the navigator drift rate. Because the analysis of the probability of collision includes a component dependent on both the terminal length and terminal accuracy, post-DSMAC GPS has the potential to affect the deconfliction solution. APL determined the changes resulting from post-DSMAC GPS and input the changes into the deconfliction simulations to quantify the effect on the probability of collision. This analysis showed that despite a small increase, the overall probability of collision remained within acceptable limits.

Tactical changes can also require deconfliction to be re-examined. To help reduce the number of missiles on a common route, the mission planners started to add altitude offsets to certain missions. A question arose about whether or not wake effects from the stacked missiles were a concern. Although aerodynamic effects were considered during the initial analysis, APL undertook a more detailed examination to answer the Fleet's question. A simulation was developed to determine the probability of a missile encountering the wake field of a previous missile. These results were fed into a second multimissile simulation to determine the overall probability within the context of a strike. The results indicated that, although a wake encounter is possible, such encounters are relatively rare. Additional analysis with a 6 degree-of-freedom simulation further indicated that the Tomahawk missile is capable of recovering from certain wake encounters. The conclusion was that no additional deconfliction measures were necessary.

As new system modifications occur, APL will continue its system engineering efforts with regard to Tomahawk deconfliction. System engineering does not stop with the delivery of the initial solution. As Tomahawk evolves, deconfliction must evolve with it to assure a low probability of collision.

## CONCLUSIONS

The Big Sky-Little Missile theory was widely accepted when APL began its deconfliction analysis. While initially valid, the theory was based on an earlier system and needed to change to fit new system developments. APL's systematic approach to deconfliction identified and analyzed the key areas of concern. Many considered the target area, dense with arriving missiles and explosive debris, the most likely area for interference, but our analysis showed such terminal fratricide was not a major concern. En route interference was considered unlikely, in part because of the Big Sky Little Missile theory. Our analysis demonstrated that GPS guidance significantly reduces the "size of the sky," leading to unacceptable probabilities of collision without some form of deconfliction. After building a consensus within the Tomahawk community supporting the need for deconfliction, APL took the lead in identifying and evaluating solutions. Potential solutions ranged from changes in mission planning to changes in weapon control to changes in the missile itself. APL's broad system perspective enabled us to recommend a solution from among the diverse set of options. We provided the analysis to define the details necessary for implementation and followed the solution through development and testing all the way into tactical Fleet deployment. The Laboratory's deconfliction involvement did not end with delivery of the solution. Deconfliction is a complex system problem. Delivery of the initial solution to the Fleet was just one step in addressing deconfliction. As the Tomahawk missile system continues to evolve, APL continues to assess how these changes affect deconfliction. APL provides continuity and breadth of knowledge to the Tomahawk program that enable us to identify and track issues, such as deconfliction, that reflect total system capabilities.

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