

# Guidance and Navigation in the Global Engagement Department

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**T**he Global Engagement Department's (GED's) mission to enhance the security of the United States often involves delivering an effect to a target accurately and predictably across a long distance. Accurate navigation and guidance are critical to this challenge. This article provides a brief tutorial on navigation, guidance, and the related concept, control. GED has made many contributions to our sponsors' navigation and guidance challenges, including accurately initializing weapon navigation systems, optimally combining multiple navigation systems to improve accuracy and to identify error contributors, updating navigation systems with predictable external references, and solving complex guidance problems. Examples in this article illustrate the breadth and depth of these contributions.

## INTRODUCTION

The Global Engagement Department (GED) hosts both the Precision Engagement and the Strategic Systems Business Areas. The combined mission of the department is to conceive, develop, and confirm integrated capabilities to maintain and improve America's ability to deter, fight, and win wars. Whether a submarine or an unmanned airborne intelligence, surveillance, and reconnaissance asset, a massive ballistic missile or a maneuverable reentry vehicle, GED considers the system from launch platform to target, supporting the entire kill chain that must operate synergistically to conduct a precision strike. Two aspects that are common to several portions of this kill chain, and that are vital to precision, are navigation and guidance. This article defines these

aspects and briefly discusses the technology behind them as well as some significant contributions that GED has made to sponsor programs in these areas. Two of these contributions are APL-developed terrain- and image-matching schemes for cruise missiles as well as integration of navigation update aids in a method developed by APL to enable accurate submarine navigation. An important part of our contribution to strategic systems is high-confidence testing and evaluation, and the APL-developed tracking techniques to evaluate reentry body accuracy have been critical to these efforts. APL also developed navigation system initialization methods for air-, submarine-, and ship-launched systems. These and other contributions are described in this article.

### APL IN KALMAN FILTER HISTORY

A history of Kalman filtering is beyond the scope of this article. However, APL was involved in the early development of the Kalman filter. APL mathematicians James W. Follin and A. George Carlton proposed, but could not prove, what turned out to be the correct structure of a Kalman filter. APL mathematician James E. Hanson proved Follin's conjecture for his particular example. Jim Follin developed what became known at APL as "Follin's variance equations." R. E. Kalman<sup>1</sup> is generally credited with obtaining a solution of the discrete-time optimal filter. Later Kalman and R. S. Bucy<sup>2</sup> collaborated on a paper dealing with the continuous-time optimal filter from a state-space point of view. Dr. Bucy had worked at APL with Follin and Hanson before collaborating with Dr. Kalman, and he dedicated his book<sup>3</sup> to James W. Follin.

### Definitions of Navigation, Guidance, and Control

Navigation is the process of determining the present state of an object, called a vehicle here for convenience, including the position, velocity, orientation, and any other relevant parameters describing the vehicle's motion. Figure 1 illustrates the differences between navigation and the related concepts of guidance and control.

The source data and mechanization of navigation differ from one vehicle type to another. For example, a surface ship can take advantage of near-continuous Global Positioning System (GPS) measurements to compute not only position but also velocity and acceleration, whereas a submarine must rely on an inertial navigation system (INS) for measurement of accelerations to compute velocity and position from some known initial conditions.

Guidance also varies greatly depending on the application. For example, for a guided weapon aimed at a stationary target of known location, guidance computes an optimal trajectory to achieve some objective, such as minimum time of flight or a steep angle of attack; an example of this is the terminal dive trajectory for the Tomahawk cruise missile. For weapons that home on a target, such as the Navy's Standard Missile, guidance commands are developed from onboard sensor measurements (e.g., a radar or infrared seeker), and guidance is the process of filtering and using these signals to intercept the target.

Control is the process of commanding a vehicle to achieve the guidance commands in the presence of unwanted disturbances (e.g., wind) and uncertainties in the vehicle model (e.g., errors in the aerodynamic characterization). Navigation, guidance, and control can be loosely or very closely coupled. A loosely coupled system might be something like a large surface ship. The ship's navigation system determines current position, speed, and heading. A fairly simple guidance calculation can be performed to determine the most efficient "great circle" route to take to reach the next desired location. The control system in this case is the ship's rudder and shaft, and orders are given to achieve the desired speed and heading indicated by the guidance calculation. A high-speed maneuvering reentry vehicle, however, requires a tightly coupled system. The vehicle can make use of measurements from an INS or GPS to navigate; at the same time, it can modify guidance commands on the basis of the updated navigation computations and simultaneously use these computations to evaluate how well the control laws are steering the vehicle, modifying the commands as errors evince themselves through the navigation measurements.

### A Brief Tutorial on INS

Figure 2 (slightly modified from Ref. 4) illustrates a "typical" configuration of an INS. An inertial measurement unit (IMU) rigidly attached to a vehicle measures motion, usually in terms of small increments of acceleration or velocity change ( $\Delta V$ ) and rotation rate or orientation change ( $\Delta\theta$ ). These are input to the navigation equations that compute or estimate position, velocity, and attitude, i.e., the "state" of the system. Thus, the vector comprising the position, velocity, and other physical quantities is referred to as the state vector. The estimated or computed state vector components are compared to measurements from a reference sensor, which will be

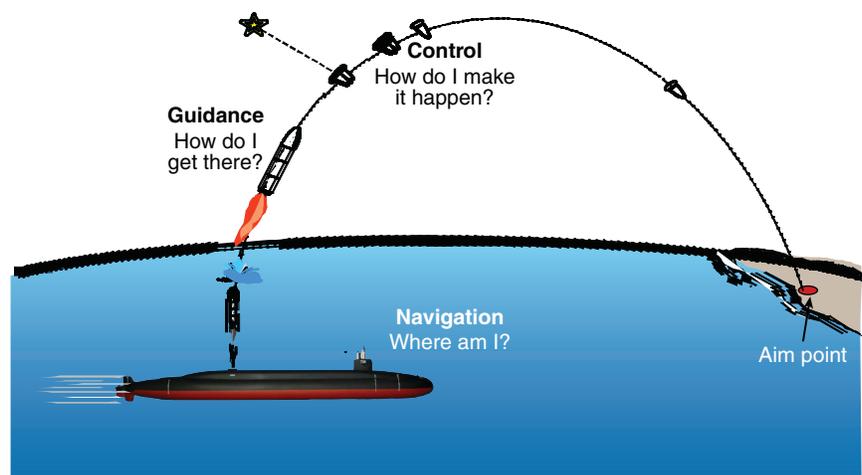


Figure 1. The differences among the concepts of guidance, navigation, and control.

corrupted by some amount of measurement error, and the differences are input to an extended Kalman filter. The purpose of the extended Kalman filter is to estimate errors in the instruments (i.e., the IMU and reference sensors), as well as position, velocity, and attitude errors that are used as navigation updates to correct instrument models and improve the navigation calculations. (The extended Kalman filter approach first linearizes the nonlinear navigation equations associated with Fig. 2 and then applies standard Kalman filter theory to the error equations. Inertial navigation tends to be very amenable to such linear approximations.)

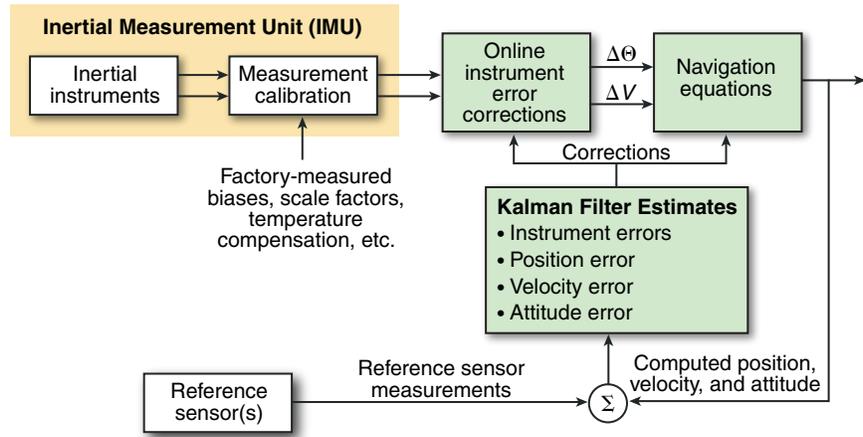
In Fig. 2, a reference sensor is used to provide a measurement of some component of the state vector, and the differences are used to update the filter. There are many methods to provide navigation updates, sometimes called “fixes,” including stellar sighting (as in the Trident II D5 ballistic missile), image matching (as in the Tomahawk cruise missile), and of course, the now nearly ubiquitous GPS. A weapon-borne navigation system can be initialized by using the navigation system on the launch platform in a process called transfer alignment.

Some of the major application areas associated with navigation and guidance are as follows:

- **Filtering:** extracting the “best” estimate of a static or dynamic variable.
- **Identification:** identifying parameters in a model or determining a model to describe the system, including the dynamic structure as well as the parameters.
- **Optimization:** determining the “best” set of parameters.
- **Test and Evaluation:** estimating the trajectory and impact point of the weapon.
- **Hardware:** developing robust, low-noise, low-bias sensors for navigation systems, considering requirements for low weight and volume and computational constraints.
- **Simulation:** demonstrating that the simplifications used to implement a navigation system are in fact good enough representations and to “fill out” the performance in regions of the performance envelope that are not tested.

### GED Contributions to Navigation and Guidance

GED contributions in these areas have generally been in the application domain, i.e., developing and testing



**Figure 2.** Typical configuration of an INS.

systems rather than advancing the theory of guidance and navigation. The following sections describe selected examples of GED contributions. The first examples relate to the reference sensors and reference sensor measurements in Fig. 2.

### NAVIGATION UPDATES

All navigation systems “drift” and must be updated. The early Tomahawk cruise missile used two methods to update the navigation system, Terrain Contour Matching (TERCOM) and Digital Scene Matching Area Correlator (DSMAC). GPS is becoming ubiquitous in U.S. weapons systems. However, loss of GPS because of jamming or other attacks on the system is a significant concern. To mitigate risk caused by loss of GPS, TERCOM and DSMAC remain part of the Block IV Tomahawk, which also includes GPS updates. (In the early 1990s, APL’s Navigation and Guidance System Integration Laboratory was developed to test the vulnerability of the Block III Tomahawk to GPS jamming. It has since been used for several other programs. Ref. 5 describes some of that work.)

The highly accurate fleet ballistic missile submarine (SSBN) navigation system uses two fix sources, GPS and bathymetric profile matching, at widely spaced intervals. The fast attack submarine (SSN) navigation system, however, is not as accurate and requires much more “help.” But frequent GPS fixes can be inadvisable for many SSN missions from a ship security standpoint, and bathymetric fixes require hard-to-establish validated “zones” over which to obtain the fix; bathymetric fixes also require a certain amount of lingering and generate noise in the water (both of which are also potentially bad for ship security). APL has developed a capability, called integrated navigation processing, to integrate all sources of navigation data in real time to improve performance.

## Terrain-Aided Navigation

Terrain-Aided Navigation (TAN) provides position updates to a vehicle equipped with an inertial navigator by determining the vehicle's location relative to the local terrain (e.g., earth, seabed, etc.). In turn, the local terrain is positioned relative to a datum (i.e., established reference grid), providing the navigator with its position on that datum. This position fixing is done by sensing the local terrain itself, often using an active measurement system such as sonar or a radar altimeter, and comparing it with a stored reference map. TAN has an early history dating from the 1950s and 1960s and was included in the development of the following systems: the APL Triton missile, preliminarily developed with a TAN system, circa 1956; the TM-76A Mace missile with the Goodyear Automatic Terrain Recognition and Navigation system, which used difficult-to-obtain radar reference images of potential target areas; and a proposed supersonic version of Regulus II missile. Important components missing from these early systems were both the capability to build reference maps over denied territory and the understanding of what makes a reference map reliable. Since the advent of modern cruise missile technology in the 1970s, APL has been a critical contributor to TAN technology and its weapon system implementations, especially in understanding the source

material used to generate reference maps and in reliably predicting reference map performance. (Refs. 6–8 provide additional details on APL's contributions to TAN.)

One TAN approach, TERCOM, was developed to update INSs for U.S. land-attack cruise missiles: air-launched, ground-launched, sea-launched, and advanced cruise missiles. In simple terms, as illustrated in Fig. 3, a TERCOM system compares a measured terrain profile to terrain profiles stored in the system computer and determines by the best match the geographic location of the measured profile. TERCOM operates on the premise that certain geographic locations on the land surface of the Earth are uniquely defined (within the local area) by the vertical contours of the surrounding terrain. It is inherently more reliable than previous radar map-matchers that attempted to match radar reflectivity maps and thus were subject to hard-to-predict reflectivity, weather, and seasonal effects. The TERCOM signal is the terrain-elevation profile itself and is a much more stable signal than reflectivity.

Because TERCOM will not work over all types of terrain, a key to reliable employment is selection of terrain that is suitable. In general, the rougher the terrain, the greater the TERCOM fix accuracy and reliability. Good terrain must also be unique. Judicious terrain selection has proved to be the key to success for TERCOM. Early

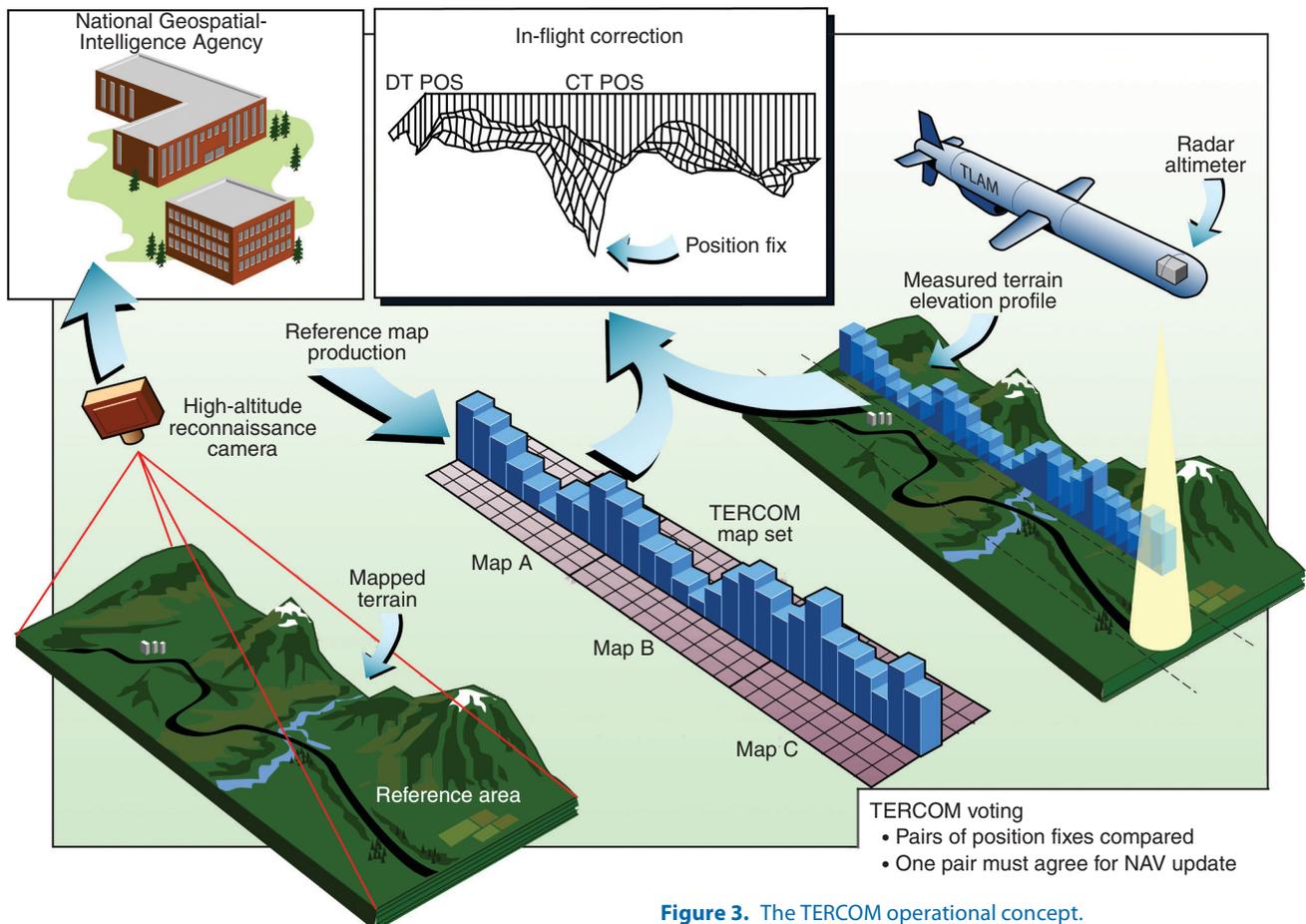


Figure 3. The TERCOM operational concept.

map-selection methodologies were developed, but flight testing indicated the need for a more reliable technique. Using data from a variety of sources, APL developed the methodology and TERCOM performance predictions that are still in use today at the National Geospatial-Intelligence Agency (NGA). From 1978 through 1992, NGA (then called the Defense Mapping Agency) was in full-rate production of TERCOM map sets. Some of those map sets, with accompanying DSMAC maps, were used in Operation Desert Storm, where 288 Tomahawk missiles were launched. TERCOM navigation was last used operationally with Tomahawk in 1998 but remains a selectable navigation mode for all variants of current Tomahawk, a critical capability as the threat of GPS jamming increases.

The Shuttle Radar Topography Mission (SRTM) provided the opportunity to exploit a new source for NGA's digital terrain elevation data and TERCOM. APL developed a novel scheme to analyze Shuttle Radar Topography Mission maps by using previous flight test data, eliminating the need for additional, expensive flight tests. A new map type was developed, the subterminal map (originally called small-cell TERCOM, or SCT), which included an APL-developed reference-map transform based on a first-return missile altimeter model. This added feature significantly reduced noise at match and produced a more robust correlation. The use of small-cell TERCOM provides increased flexibility in mission planning for all Tomahawk variants that use TERCOM navigation updates, using, in part, the APL-developed fix accuracy estimator for SCT. Additionally, SCT eliminates the need for NGA-produced TERCOM maps and significantly decreases the time needed to produce missions. The new SCT-size TERCOM maps have been used successfully in flight tests by all three U.S. strategic cruise missiles: Tomahawk, air-launched cruise missile, and advanced cruise missile. The new TERCOM planning capability has been implemented in the Tomahawk Planning System and became operational in FY2007.

Advances in the technology of remote Earth sensing and the development of advanced radar altimeters enable a more accurate TAN method, called precision terrain-aided navigation (PTAN), where the concept of TERCOM has been extended to much higher resolution and accuracy. APL has been a major participant in the PTAN flight test design and has analyzed all the flight test data collected to develop the database needed to fully develop a PTAN map-selection methodology complete with prediction of map reliability and of fix accuracy. APL also developed a detailed PTAN radar model for accurate prediction. In addition, APL is examining the potential source materials that could be used to provide the small-resolution reference maps that will provide a true precision navigation capability. Understanding the characteristics of each of these sources is essential to predicting PTAN performance.

APL contributed significantly to TAN from the beginning of its application to U.S. cruise missiles and has made the key contributions that have been and continue to be critical to their successful employment. Of particular note are APL's map-selection methodology and the recent capability to produce maps wholly within the Tomahawk Weapon System. GED's Mission Planning Development Laboratory contains the most comprehensive set of digital terrain elevation data databases, flight test telemetry, and analysis tools in the world, and APL is applying these for advanced TAN development.

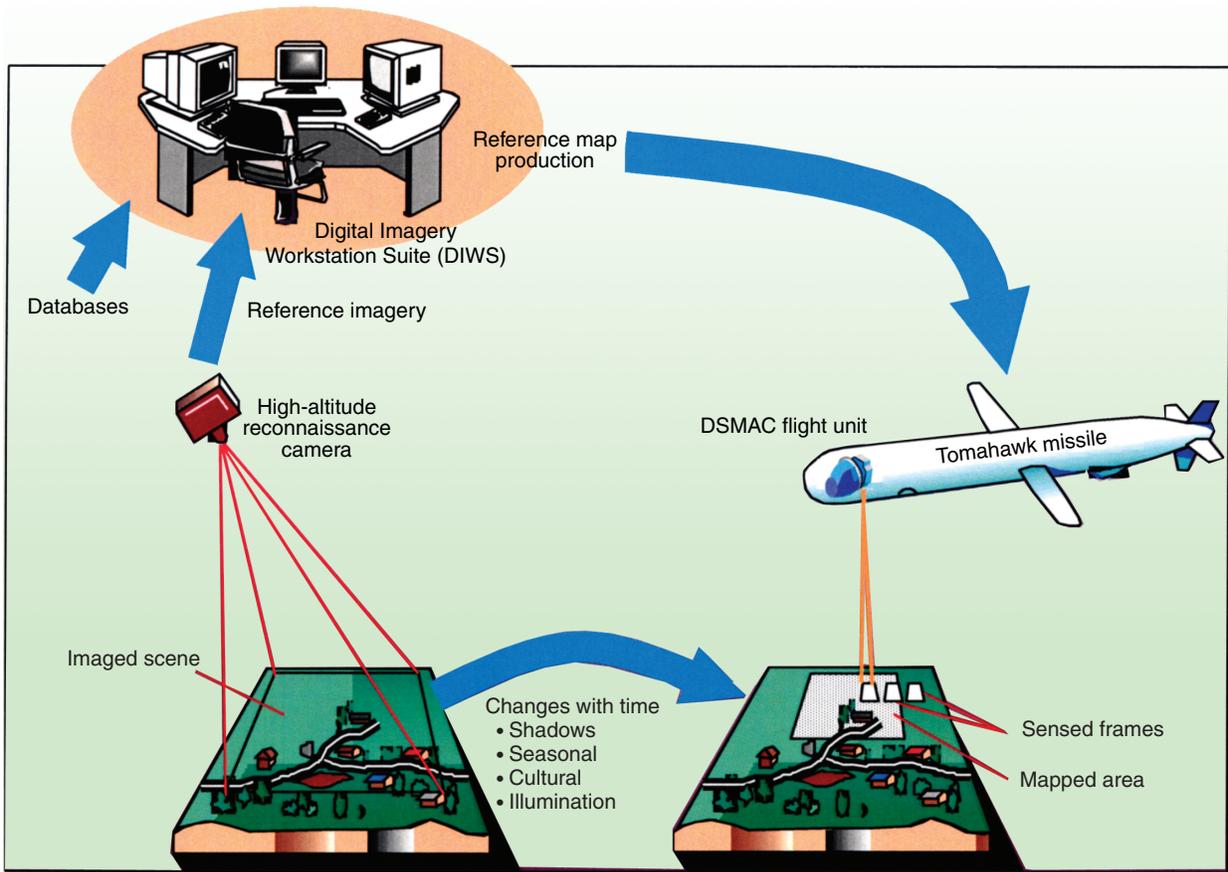
### Navigation Updating via 2-D Scene Matching

Another example of a navigation system updating method is APL's version of 2-D scene matching, DSMAC. DSMAC has been used by three generations of the Tomahawk cruise missile to provide reliable, accurate position measurements. At a high level, DSMAC operation is fairly simple. To provide a position update during missile flight, the DSMAC system takes pictures of the ground. These sensed images are compared with stored reference images, and the best match is used to determine the current missile position.

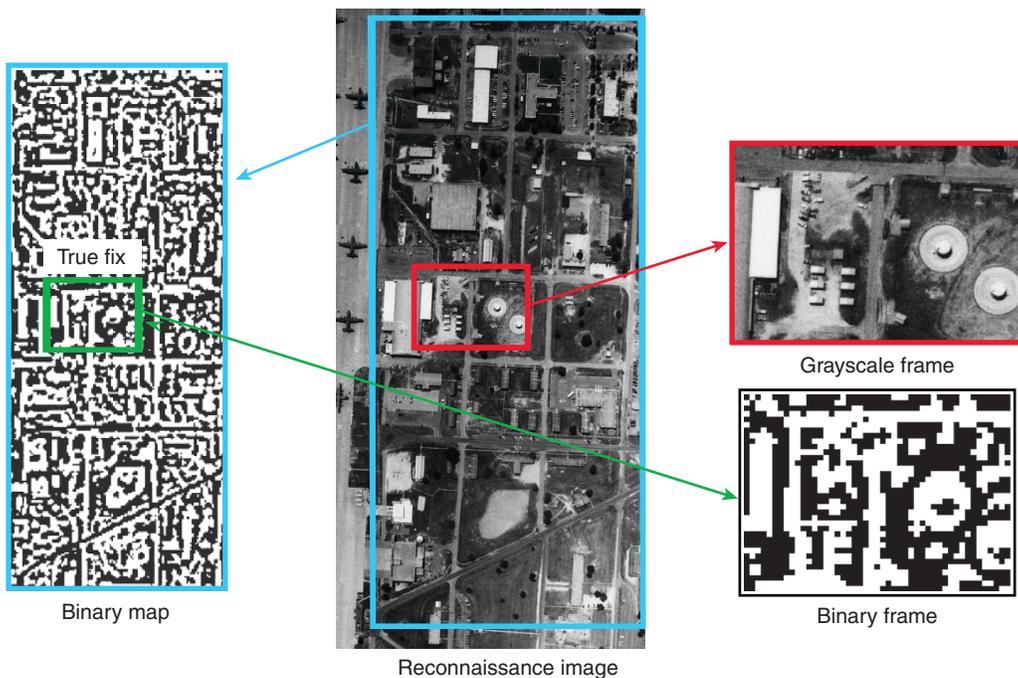
Figure 4 depicts the activities involved in DSMAC employment. The activities on the left occur before the actual missile flight and are collectively referred to as mission planning. Mission planning is responsible for selecting a suitable location for the DSMAC update, acquiring a reconnaissance image, processing the image to produce a suitable DSMAC reference map, and packaging the reference map with the required support data. The right side of the figure shows DSMAC operation during the missile flight. The DSMAC flight unit acquires a sequence of images, known as sensed frames, compares these frames to the reference map, and determines the missile position on the basis of this comparison.

The DSMAC flight unit consists of a sensor, a processing unit, and a flash unit to provide scene illumination. DSMAC begins acquiring images before reaching the scene area selected by mission planning, and it continues taking pictures past the scene area. To enable efficient computational algorithms and to help suppress lighting differences between the sensed and reference images, the images are converted to binary. Figure 5 shows a sample grayscale sensed frame and the result of the binary conversion.

Comparison of a sensed frame with the reference involves an algorithm known as binary correlation. For each possible location of the sensed frame within the reference, binary correlation computes the correlation level by counting the number of points at which the binary values in the frame and reference agree, thus creating a correlation surface. The maximum value in the correlation surface is referred to as the correlation peak and corresponds to the best match between the frame and the reference. Whether the correlation



**Figure 4.** The parts of the DSMAC system. The activities on the left side of the image produce the products needed for DSMAC operation, and they are collectively known as mission planning.



**Figure 5.** DSMAC operation. The center image was captured over Eglin Air Force Base. This image was processed to produce the binary reference map on the left. A simulated frame and the corresponding binary are shown on the right. The green box over the reference map shows the position at which this frame matches the reference.

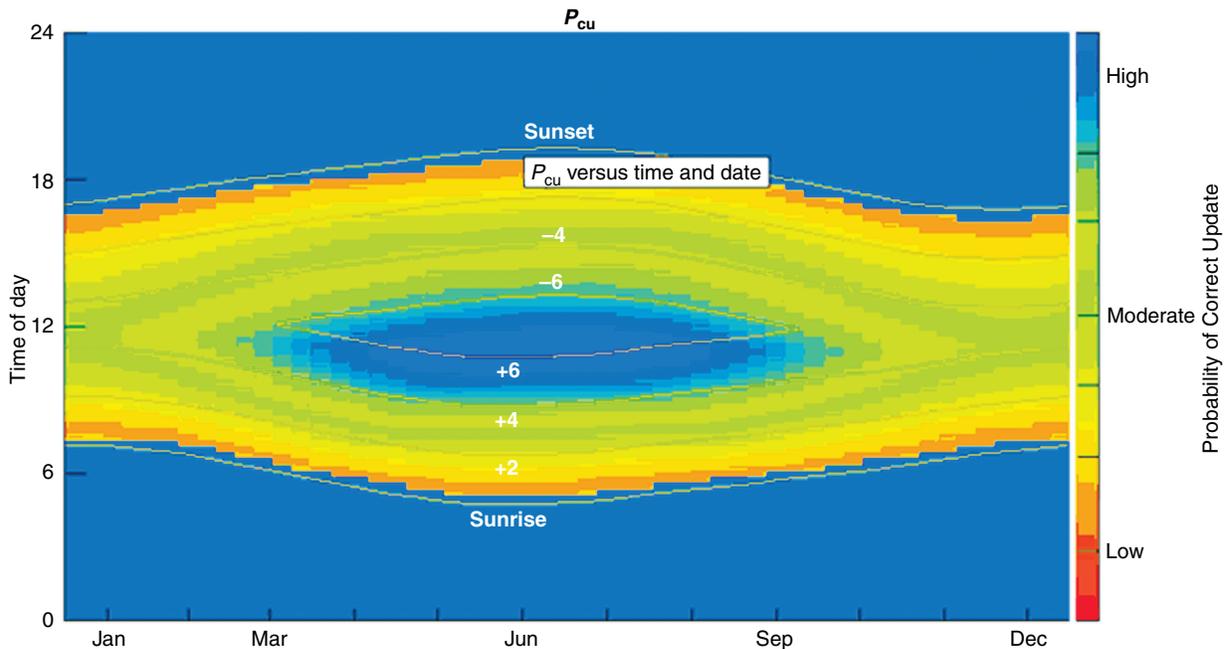
peak occurs at the correct location depends on whether any of the correlation levels away from the peak, called sidelobes, are larger than the peak. The original DSMAC algorithms protect against a false fix by considering each set of three consecutive frames and asking whether two out of the three correlation peak positions are consistent with the known missile velocity (a process called voting), assuming that two false fix locations are not likely to be consistent.

During the late 1980s, APL proposed two significant improvements to the DSMAC algorithm. The first was a new algorithm for converting the grayscale images to binary. The new algorithm preserves more scene information and allows a closer match between the processing of the reference map and the sensed frames, leading to a higher peak correlation level and increasing the likelihood of a true fix. The second significant change introduced by APL was the introduction of coherent correlation surface summation to replace voting. Coherent surface addition shifts the individual correlation surfaces so the peaks will line up, and then it averages the shifted surfaces; the result is known as the summed correlation surface. This process can produce a peak in the summed surface even though there was no peak in any of the individual surfaces. The sidelobes are reduced without affecting the average peak level. Correlation surface addition provides a significant improvement in DSMAC performance.

The operational concept for the Tomahawk cruise missile requires a high confidence that the missile will arrive at the target with the required accuracy. As a

result, the mission planning effort for DSMAC has two functions. First, mission planning must produce the data required to execute the in-flight DSMAC update, a rather straightforward process. Second, mission planning must estimate the probability of a correct update, which is part of the calculation of the probability that the missile will arrive at the target. To calculate the probability of a correct update, mission planning must determine the likely impact of a variety of environmental factors on DSMAC performance. Mathematical models are used to predict performance, which can vary with time of day and season (see Fig. 6). The first versions of the DSMAC performance-prediction algorithms were developed and subsequently improved by APL on the basis of the physics behind DSMAC operation, combined with a detailed analysis of flight test data under a variety of conditions.

Current Tomahawk operations place an emphasis on responsive planning. To respond to this emphasis, APL currently is involved in an effort to update the DSMAC performance-prediction system. Previous implementations of DSMAC performance prediction required custom-built hardware to support the computational load. APL developed an approach to the prediction algorithms and prototyped the computationally expensive portions of the algorithm to demonstrate that they could be re-hosted on commercial off-the-shelf hardware. APL also modified several of the algorithms to better reflect the analyst's goals, introduced new approaches to reduce the effort required by the analyst, automated portions of the system that had required analyst interaction, and restructured the task flow. The changes are intended to



**Figure 6.** Predicted probability of DSMAC update throughout the year. The probability of correct update ( $P_{cu}$ ) values in this figure illustrate the changes in performance as a function of missile flight date and time (hours after sunrise or before sunset) for a reference image acquired in June and are not based on a real scene.

provide an easier-to-use system that significantly reduces the time required to plan DSMAC missions.

### Optimal Navigation Sensor Integration

In order to optimally integrate INS outputs with external sensors used for navigation aiding, detailed error models for the INS sensors, the navigation sensors, and any other systematic error sources must be obtained. Error models are mathematical descriptions of the fundamental error sources in a system, how they interact in an implemented system, and how they propagate in time. For example, one of the primary sources of position error in an INS is caused by gyro bias drift. A complete INS error model would include the expected magnitude and error structure of the gyro bias drift, how this error propagates in time, and how it contributes to errors in the desired INS position, velocity, and attitude outputs. Since navigation sensors are not perfect, validated error models for them must also be obtained. Mathematical descriptions of any other uncompensated errors in the system must be available; for example, local vertical deflections of gravity under certain conditions can be a very large contributor to errors in the outputs of an INS.

The error models and measurement data from the INS and the navigation sensors are all processed with a Kalman filter, which optimally estimates the errors in the INS as well as errors in the navigation sensors. Once the errors in the position, velocity, and attitude of the INS are estimated, they can be corrected from the observed INS outputs, providing an improved optimally integrated solution. If the errors in the INS are stable, then the INS is effectively calibrated with the use of the navigation sensor data. Therefore, one of the advantages of this type of navigation sensor integration is that continuous corrections to the errors in an INS can even be made (although with somewhat less accuracy) when the navigation sensors are not available. A schematic of this process is shown in Fig. 7.

APL has developed a framework within which to instantiate the process for any set of error models,

permitting optimal sensor integration to be performed on different platforms with different sensor suites all within the same flexible architecture. The framework allows simultaneous integration of multiple inertial navigation systems, various navigation aid sensors that provide position, velocity, and attitude reference information. The flexible Kalman filter architecture is developed in Matlab. For platform integration, the Matlab software is compiled and integrated with sensor interface and preprocessing software. The software is configurable for various inertial systems, navigation sensors, and mission-unique scenarios.

As an example, one sensor successfully used as a navigation aid for underwater vehicle navigation is a DVL (Doppler velocity log). A DVL can provide very accurate velocity-over-ground information by acoustically tracking the ocean bottom while the underwater vehicle is in fairly shallow water and traveling slowly. In most applications, the DVL is used to permit dead reckoning from a known position by using the accurate DVL velocity information. (Dead reckoning is the process of estimating the position of an airplane or ship solely on the bases of speed and direction of travel and time elapsed since the last known position.) The DVL has misalignment, bias, and scale factor errors that result in dead-reckoned position errors that tend to grow as a function of the total distance traveled. Because the errors in the DVL are most significant along the underwater vehicle track, frequent course reversals can cancel out most of the errors, so the position error growth is bounded. The DVL errors for straight-line transits, however, are not bounded. With an error-model-based Kalman filter integration approach, the errors in the underwater vehicle's INS data can often be readily observed in the DVL data. Likewise, many of the errors in the DVL can be observed in the inertial navigation data.

Once the errors in an INS are optimally estimated, these errors can be subtracted from the observed inertial outputs to form an improved position track. Optimal sensor integration, as described here, has been successfully deployed by APL on various platforms.

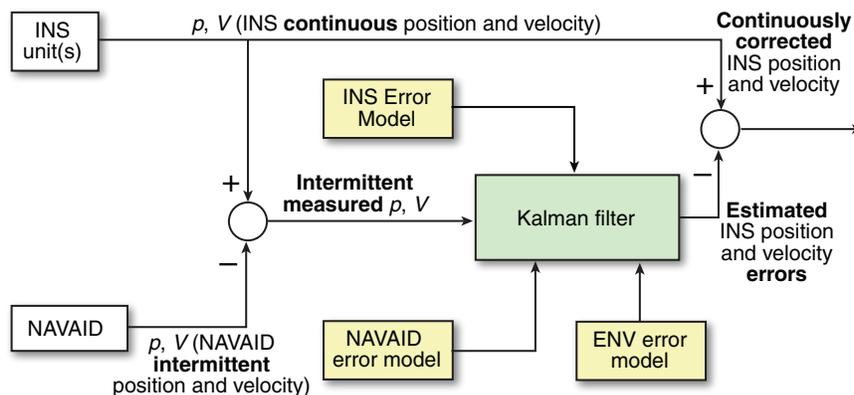


Figure 7. Using a Kalman filter to optimally integrate sensors to aid navigation.

### VEHICLE TRACKING

APL's performance assessment of the Trident II D5 guidance inertial measurement unit (IMU) is done at what is known as the "level-3" domain, or component level errors such as a gyro scale-factor error. (Level-1 errors are total weapon system miss and level-2 errors are package level errors, such as navigation-subsystem velocity error.) That is, the instrumentation built into the

system is sufficient to allow parameter identification and estimation at the level of individual guidance component errors such as accelerometer scale factor, gyro bias drift, and mass imbalance terms, among many others. APL was a strong contributor to the development and adoption of the required instrumentation suite (see, for example, Ref. 9 on the development of the satellite tracking, or SATRACK, system), providing expertise in areas ranging from the required mathematical modeling to hardware development. Below, we discuss a few of the major components of this instrumentation.

### Submarine Tracking

Missile flight tests from submerged launch platforms provide some unique challenges. Accurate tracking of the submarine in real time and for post-mission evaluation is essential. APL has made significant contributions in this area for the Trident II D5 Strategic Weapon System.

### Demonstration and Shakedown Reference Navigation System

The demonstration and shakedown (DASO) reference navigation (DRN) system was designed and developed by APL to provide a reliable and highly accurate real-time determination of an SSBN's position and velocity using GPS. It is used in conjunction with the existing Test Instrumentation (TI) Mast, which provides UHF communications during launch. The DRN system is used for range safety during DASO operations, to collect data for post-DASO analysis of navigation sub-

system performance, and for determination of weapon system initial condition errors at the time of missile launch (see *Integrated Prelaunch Processor*). The position information from DRN is used to accurately predict the location of the missile at broach, so that it can be rapidly acquired by the Eastern Test Range tracking assets, and to precisely determine the submarine geodetic position at launch. The DRN system also provides a highly accurate position reference system to support any desired special tests.

The DRN units consist primarily of a laptop computer, GPS receiver, and external antenna atop the TI mast (see Fig. 8). Also connected to the DRN computer are a printer and remote display. The GPS receiver is an AN/PSN-11 Precision Lightweight GPS Receiver (PLGR), a P/Y-code receiver equipped with a tamper-proof security module. The PLGR is a hand-held GPS receiver widely distributed throughout the armed forces. The DRN stack installed on the SSBN contains redundant GPS receivers and laptops as well as additional spare parts, and the TI mast has redundant antennas.

The estimated real-time accuracy of the DRN output greatly exceeds the required DRN real-time accuracy and even the much tighter required post-mission accuracy. GPS data recorded at the DRN station located in the APL Cape Canaveral Field Office are used for post-mission differential correction. The accuracy of the post-mission corrected DRN data is approximately twice that of the real-time solution. Improvements to the DRN system now in progress at APL, leveraging receiver and

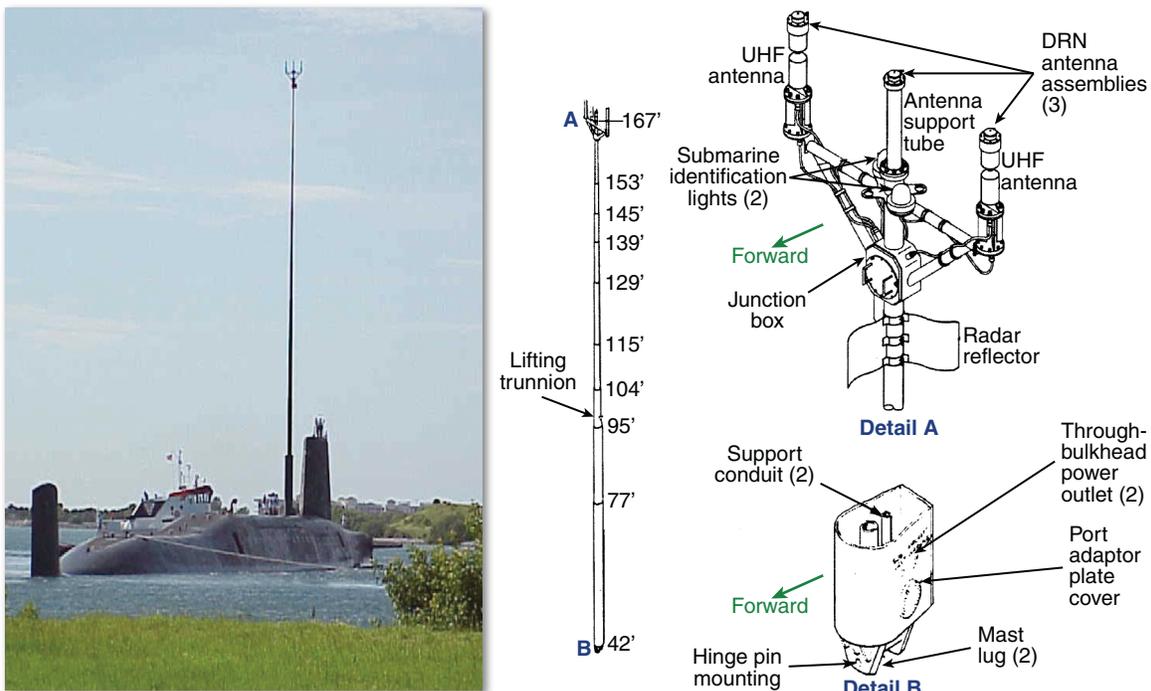


Figure 8. TI mast and DRN antenna assembly.

computer advances and the Wide Area Augmentation System, are planned to make the real-time accuracy of the system even better.

### Position Reference System

The position reference system was designed and developed by L-3 Interstate Electronics Corporation to provide a reliable real-time determination of an SSBN's position using bottom-mounted deep ocean transponders (DOTs). These DOTs are deployed from a surface ship and surveyed by using GPS receivers and an acoustic transponder aboard the vessel. APL personnel ride the ship during the survey both to provide assistance and to perform the post-survey validation. APL's role has been to develop requirements, validate the system performance, and make recommendations as to system modifications and array geometries. APL also is currently designing and implementing new Kalman filter-based survey software to process the GPS and acoustic data collected to improve the survey accuracy.

The submarine "listens" for acoustic returns from the DOTs (see Fig. 9) and uses the resulting two-way travel times in conjunction with an accurate DOT survey and a rudimentary sound velocity profile to determine position and velocity in real time. Post-mission, APL uses a detailed sound velocity profile, spherical ray tracing, and automated editing to produce a precise submarine track used to evaluate the real-time solution and support initial condition error estimation using the integrated prelaunch processor (IPP).

### Integrated Praelaunch Processor

Precise submarine tracks produced by the DRN (see *Demonstration and Shakedown Reference Navigation System*) or position reference system (see *Position Reference System*) systems are differenced with the position data from the submarine master navigation system to form a measurement stream into the IPP. The IPP is a 297-state modified Bryson Frasier Kalman Filter

Smoother implemented in sparse matrix form that produces extremely precise estimates of initial position, velocity, and orientation errors as transferred to the Trident II missile. Initial condition errors are a key part of the Trident II error budget because the missile does not rely on an external measurement source such as GPS. The IPP is an essential component of APL's multi-phase combining approach to error estimation, complementing the SATRACK process (see *Vehicle Tracking*) to enable error estimation at the level of the individual component errors (level-3 errors, as described above). The combination of methods has revealed errors in the system such as launch-point-specific vertical deflection errors that cannot be determined with one method alone.

### NAVIGATION SYSTEM INITIALIZATION

Transfer alignment is a scheme to initialize a weapon's INS by using the navigation system of the launch platform and to improve weapon system INS performance by compensating for navigation and instrument errors. Transfer alignment is implemented by matching the weapon system's state estimates to a time sequence of state measurements derived from a more accurate launch platform. Figure 2 illustrates this process; the reference sensors in that figure are the sensors in the navigation system on the launch platform.

The transfer alignment assumes that the launch platform provides weapon state information with well-characterized accuracy. During transfer alignment, errors in the launch platform's knowledge of the weapon's state are passed along to the weapon system; if these errors are not accounted for in the weapon's Kalman filter, they could be incorrectly characterized as instrument errors. Thus, characterization of these errors and weapon system INS instrument errors is part of the transfer-alignment design process. Another key part of the design process is selecting the matching states.

Transfer alignment is important when launching from aircraft and other flight vehicles, ships, and submarines. In the maritime regime, APL has contributed to developing alignment methods for the Tomahawk.

### Tactical Air-Launched Weapon Transfer Alignment

In support of GED's tactical aircraft programs, APL engineers were tasked to design a transfer-alignment scheme for a notional wing-mounted, air-launched weapon with an inexpensive INS. The alignment scheme had to meet a very tight

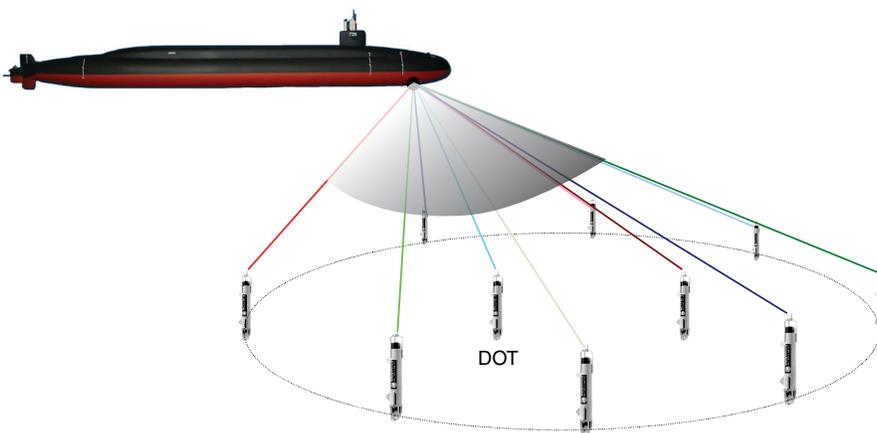


Figure 9. DOT array.

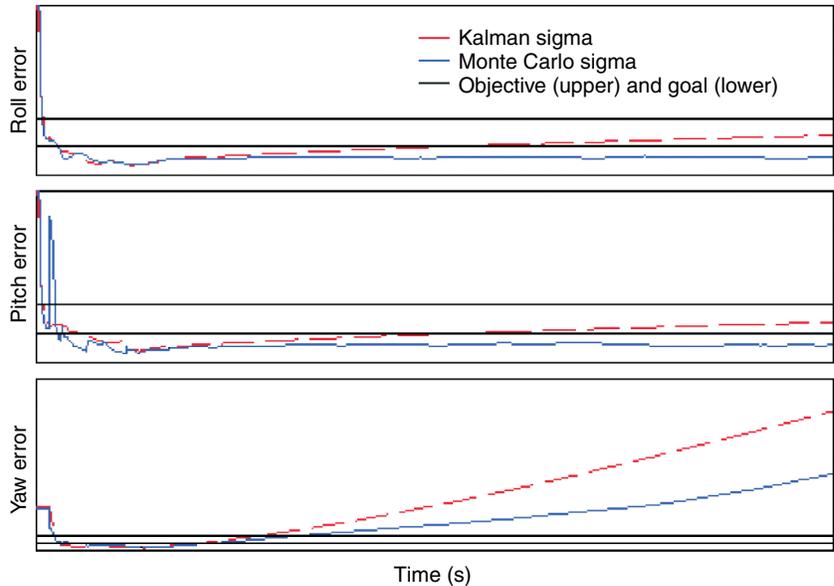
attitude initialization accuracy requirement, and the goal was even more aggressive. APL developed a Monte Carlo navigation simulation that included an aircraft-trajectory generator, a stochastic aircraft INS model, an aircraft-communications model that simulates timing features of the transfer-alignment message, a wing and mount motion model, and a weapon INS model. Using the simulation, APL performed trade studies to identify the key transfer-alignment error sources and design a robust transfer-alignment scheme.

APL evaluated three measurement options: position matching, velocity matching, and position plus attitude matching. The names of these options refer to the weapon navigation-state estimates provided by the aircraft for use as reference measurements. Theoretically, velocity matching has the advantage of being simple to implement, and alignment can be achieved quickly; however, velocity matching is sensitive to noise effects such as vibration, and it does not correct position biases. Position matching corrects position biases, and it is less sensitive to noise than velocity matching because of the inherent filtering associated with integration. Unfortunately, integration also introduces lag in the system, so alignment is typically slower than that with velocity matching. As expected, the position matching scheme effectively corrected the initial position and velocity errors. Attitude estimates were improved during an alignment maneuver, which increases the observability of the Kalman filter error states; however, during nonmaneuvering flight, the attitude errors grew at approximately 15°/h because of loss of observability in the yaw channel, which prevents an accurate estimate of the yaw gyro bias. The residual yaw gyro bias causes the large yaw error drift shown in Fig. 10.

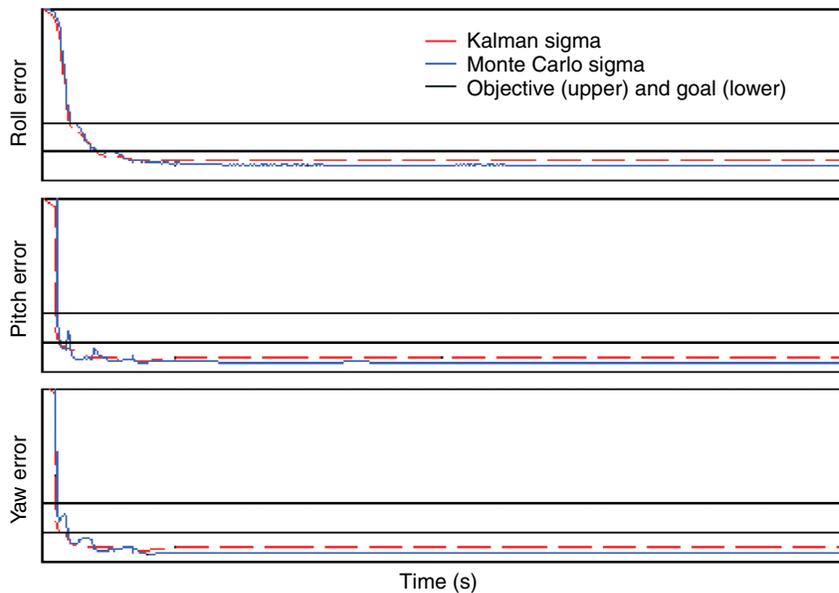
To improve attitude performance, APL added attitude matching to the existing position-matching transfer-alignment scheme. Figure 11 illustrates the improved attitude-estimation performance of the position- and attitude-matching scheme.

Figure 11 displays very good agreement between the standard

deviation of the Monte Carlo error and of the Kalman filter error estimate. Approximately 42 s after the alignment maneuver is initiated, all of the attitude errors meet the alignment-accuracy goal. In addition, all attitude errors remain below the attitude-accuracy goal for the remainder of the flight, which illustrates one of the major benefits of attitude matching. Further, simulation analyses indicated the scheme was robust to message time tag errors, aircraft INS accuracy degradation, aircraft INS position resets, data latency, aircraft wing-vibration levels, transfer-alignment rates, and the flight durations



**Figure 10.** Attitude-state estimation performance by using a position-matching approach for transfer alignment.



**Figure 11.** Attitude-state estimation performance by using a position- and attitude-matching approach for transfer alignment.

considered. Data latency, vibration levels, weapon IMU in-run bias stability, and transfer-alignment rate were the strong performance drivers.

The transfer-alignment design architecture is flexible. The extended Kalman filter can be tuned, or additional states can be easily added as the need arises. Tuning and filter modifications typically occur after flight testing, which uncovers unexpected error sources and error behavior; thus, flexibility and tune-ability are important characteristics of an alignment scheme design. Additional details of this work can be found in Ref. 10.

APL engineers briefed the transfer-alignment design to the government sponsors and one of their weapon contractors. The weapon contractor now uses the APL scheme on some of its programs.

## MISSILE GUIDANCE

### Tomahawk Terminal Guidance System Improvements

APL's assessment of the Tactical Tomahawk guidance and control algorithms was performed by using an APL-developed high-fidelity 6-degree-of-freedom simulation called TT-OO6DOF. Although certain models used in the simulation are obtained from the missile developer, such as the aerodynamics and engine models, the vast majority of the simulation was developed independently by using physics and design intent. This approach enables APL to identify implementation errors as well as performance problems. Using TT-OO6DOF, APL emulated missile performance from boost to impact over various nominal and extreme conditions, by using both deterministic and Monte Carlo methods. As a direct result of these analyses, APL has made numerous contributions to the Tactical Tomahawk program. One notable contribution was the performance assessment and improvement of the Tactical Tomahawk terminal-maneuver guidance logic.

Tactical Tomahawk is launched against a target at a known location and via a desired impact angle. The missile guidance logic accomplishes this task by dynamically sizing an appropriate terminal-maneuver ellipse, based on predicted maneuverability, and then guiding the missile to fly along this ellipse and into the target at the desired impact angle, as shown in Fig. 12. The guidance logic is flexible enough to support a low-altitude ingress, such that the missile pulls up onto the terminal ellipse, as well as a high-altitude ingress where the missile descends rapidly toward the terminal ellipse. In assessing the Tactical Tomahawk terminal-maneuver performance, APL noted that there were a number of ingress conditions (i.e., the combination of the missile's altitude, speed, and weight upon approaching the terminal maneuver, along with the atmospheric conditions) from which terminal-maneuver performance at certain desired impact angles resulted in an unacceptable terminal

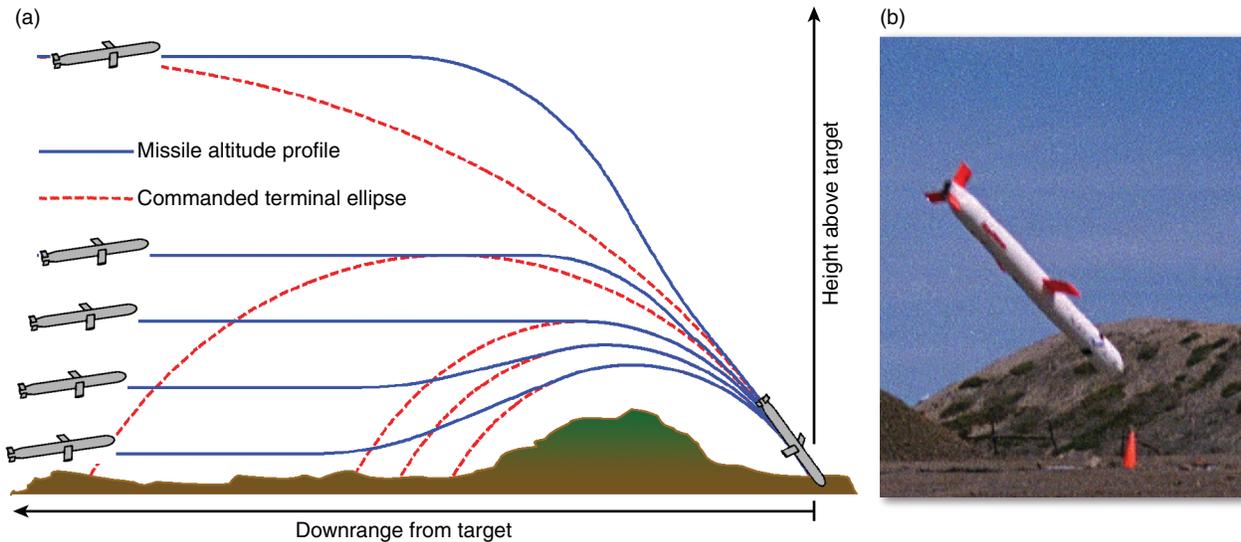
miss at impact. For each of these problematic conditions, APL isolated the cause of the terminal error and, either independently or in collaboration with engineers from the missile developer, created modifications and improvements to the terminal-maneuver guidance logic.

One example of APL's direct involvement in improving Tactical Tomahawk terminal-maneuver performance was the implementation of a dynamic radial rate limit that allowed the missile to successfully perform shallow-dive-angle maneuvers from high-ingress altitudes. Figure 13 shows a block diagram of the terminal-maneuver guidance logic during this descent, which dictates the commanded acceleration of the missile normal to the missile body,  $A_{z_{Cmd}}$ . As shown, the total normal acceleration command is generated by a summation of a "nominal" acceleration command,  $A_{z_{Nom}}$ , and a closed-loop regulator component to reduce the position error between the missile and the ellipse. The nominal acceleration command ( $A_{z_{Nom}}$ ) is simply the acceleration normal to the ellipse that a point mass traveling at the same speed as the missile would need to trace out the shape of the ellipse.

Although  $A_{z_{Nom}}$  assists the missile in following the desired trajectory, it is the regulator component that dominates when the missile is relatively far from the commanded ellipse. The regulator component is a feedback control system with rate damping to minimize the position error between the missile and the ellipse. As the missile descends toward the ellipse, it is imperative that the guidance logic does not allow the missile to "overshoot" the terminal ellipse. Doing so could result in a premature impact with the terrain, thus wasting a missile and leaving a target intact. To mitigate the possibility of "overshooting" the commanded ellipse, the missile developer added a lower limit,  $\dot{R}_{Min}$ , to the radial rate command. This radial rate lower limit was empirically derived on the basis of the missile's ability to arrest a descent rate.

During analysis of Tactical Tomahawk terminal-maneuver performance, APL engineers found that the described terminal-maneuver logic resulted in unacceptable terminal performance for shallow-impact-angle,  $\gamma_{impact}$ , maneuvers from very high altitudes. Upon further investigation, APL engineers found that the existing radial rate limit,  $\dot{R}_{Min}$ , was unnecessarily conservative. If the missile started too high above the ellipse, this unnecessarily conservative radial rate lower limit restricted the ability of the missile to approach the ellipse, resulting in large terminal error (see Fig. 14a). Thus, the missile was denied the ability to perform a significant set of useful terminal maneuvers, namely shallow-impact-angle maneuvers from high-altitude loiters.

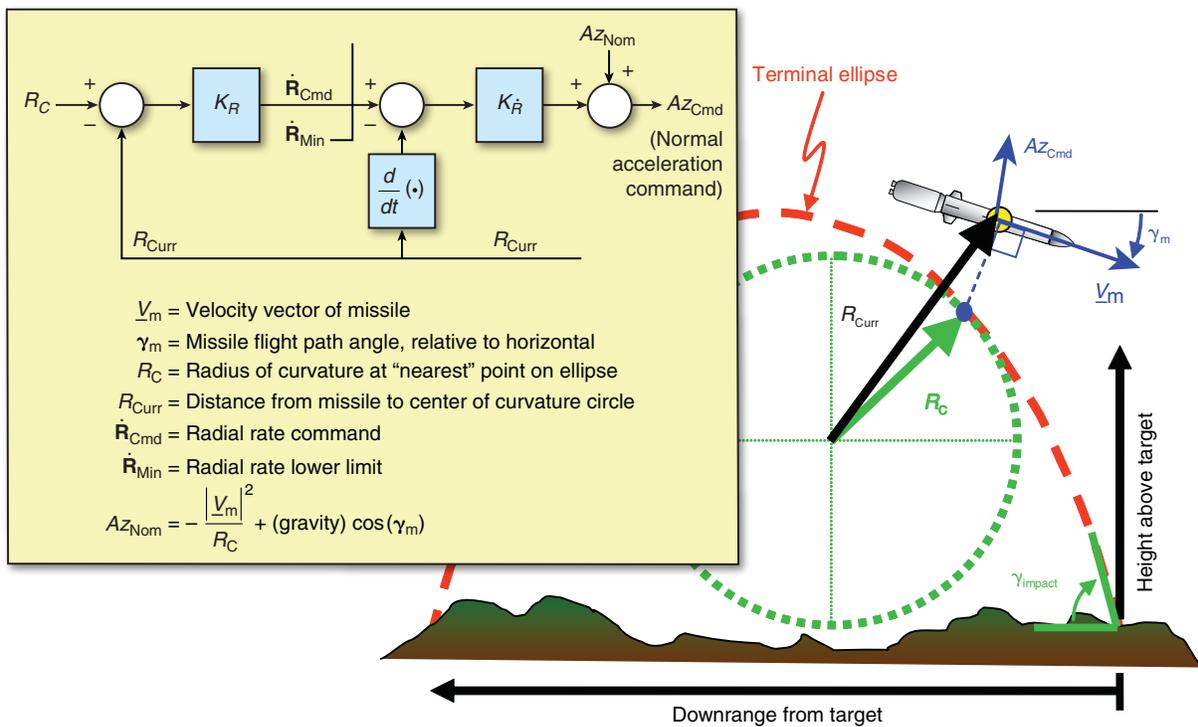
After identifying the cause of the problem, APL developed a solution that both improved performance and was readily implemented in the established control architecture. To achieve a balanced descent rate that



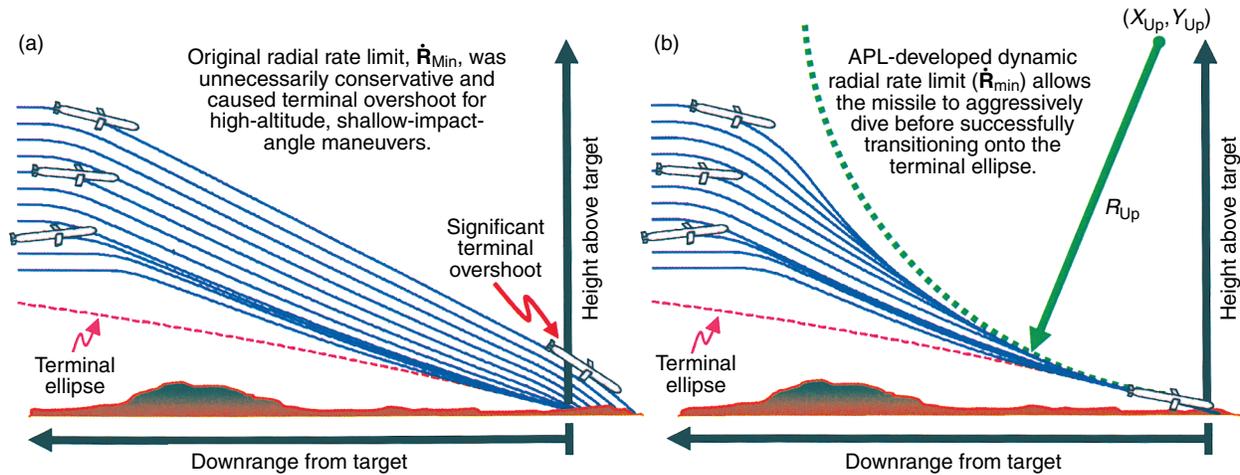
**Figure 12.** (a) The Tactical Tomahawk cruise missile impacts a target at a specified dive angle, irrespective of ingress conditions, by dynamically sizing an appropriate terminal ellipse. (b) Tactical Tomahawk performing a terminal dive during a test flight. (Photo courtesy of the U.S. Navy.)

was aggressive enough to allow the missile to approach the ellipse from very-high-ingress altitudes while still guaranteeing that the missile will be able to arrest that descent rate as it approaches the ellipse, APL derived a dynamic radial rate limit that gracefully guides the missile along a steep flight-path angle toward the ellipse and then approaches the ellipse via a prescribed pull-up arc. With this APL enhancement to the terminal guid-

ance logic, if the missile has an exceptionally large radial error to the ellipse, the guidance logic will define a radial rate limit that essentially guides the missile along a flight path that is tangent to a pull-up circle, which is in turn tangent to the prescribed terminal ellipse (see Fig. 14b). The missile guidance logic uses the law of energy conservation to estimate what its speed, and hence acceleration capability, will be when it approaches the terminal



**Figure 13.** Tactical Tomahawk terminal-maneuver guidance logic dictating the normal acceleration command to regulate the radial position error from the terminal ellipse



**Figure 14.** (a) With the original radial rate limit,  $\dot{R}_{Min}$ , Tactical Tomahawk was limited in its ability to successfully engage targets via a shallow impact angle from high altitudes. (b) With the APL-developed dynamic radial rate limit, the missile can successfully transition to shallow terminal ellipses even from high altitudes, adding an additional capability to an already capable weapon.

ellipse, and uses this projected acceleration capability to determine the radius ( $R_{Up}$ ) and center ( $X_{Up}$ ,  $Y_{Up}$ ) of the pull-up circle. As the missile approaches this pull-up circle, the guidance logic can use simple geometry to determine the desired flight-path angle necessary to fly along a line tangent to this pull-up circle. After the missile is sufficiently close to the pull-up circle, the guidance logic uses similar geometry calculations to determine the desired flight-path angle, and hence radial rate limit, necessary to pull up onto the terminal ellipse via the described pull-up circle.

This APL-developed terminal guidance logic enhancement has been implemented in the Tactical Tomahawk flight software and enables the missile to perform shallow-impact-angle terminal maneuvers from high-ingress altitudes by descending aggressively toward the terminal ellipse and pulling up onto the ellipse along the prescribed pull-up circle. This and other APL-developed guidance improvements make the Tomahawk weapon far more robust and accurate across its performance envelope.

## SUMMARY

The examples in this article describe only some of GED's applications of navigation and guidance concepts. The overall goal is to improve weapons system accuracy in all environments, including the presence of countermeasures. Current operational concerns regarding collateral damage dictate even higher accuracy and robustness for our weapons.

In the future, we expect that our adversaries will likely be more mobile and will attack our key infrastructure. As a result, our forces will need to be more flexible, agile, and mobile. Reducing the size and weight of navigation devices while maintaining highly accurate performance will be even more important, especially

for navigation devices for individual soldiers. As the threat to GPS increases, navigation without GPS will be increasingly important. Also, the current GPS system requires near line-of-sight to the satellites, precluding operation indoors or underground (or underwater, as has been described). Innovative navigation methods will have to be developed to solve these challenges.

GED's navigation and guidance innovations are currently in the hands of operational users, making a difference in current conflicts and other operations. As we proceed to the future, GED will continue to test weapon system performance with high precision and confidence. And we will continue to develop innovative applications that improve both current and new weapons that will ultimately enhance the security of our nation.

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