Systems Analysis and Test and Evaluation at APL

Larry J. Levy

Systems analysis and test and evaluation are a part of almost everything we do at APL. Systems analysis is discussed in this article in terms of operations analysis and architectural analysis, the front-end activities of the systems engineering process. Test and evaluation is examined in terms of test environment and instrumentation, test data acquisition and evaluation, and system performance and readiness evaluation. Both are described in terms of their systems application, with emphasis on their inherent science and technology. The Laboratory's strengths in this area are in the facilities, simulations, and instrumentation capabilities that are grounded in our operational experience and the systems engineering approach.

INTRODUCTION

Systems engineering is a primary activity of APL. We *analyze*, design, develop (sometimes build), integrate, and *test and evaluate* complex operational systems. Systems analysis and test and evaluation (SA/T&E) can be thought of as the first and last activities in the systems engineering process and are a part of almost everything done at the Laboratory. In a broad sense, "systems analysis" is an engineering technique that breaks down complex problems into basic analyzable elements with known analyzable interrelations. However, we restrict its use here to the "front end" of the systems engineering process to primarily refer to "operations analysis" (requirements, objectives, concept of operations, etc.) and "architectural analysis" (functional and trade-off analysis, subsystem definitions, etc.). "Test and evaluation" is a process of experimentation with a working system (or simulation) to determine (model) its characteristics. There is considerable overlap in the functional activities of systems analysis and T&E, as shown in Fig. 1. If one considers T&E as a system in itself, then the front end of the T&E development process contains the functional elements from systems analysis.

This functional breakdown could be the method for describing the SA/T&E area at APL. However, other breakdowns are possible such as system purpose (scientific, tactical, strategic), stage of system acquisition (concept exploration, demonstration and validation, development, and postdeployment), APL's role (research and development, limited production, Technical Direction Agent [TDA], independent evaluator), and systems application (space systems, strategic deterrence, strike, air defense, undersea warfare, communications, aeronautics, biomedical, transportation). The method used for this article is presented in terms of systems application, with emphasis on the inherent science and technology (S&T) and the scope of each effort. An introductory summary of the history, programs, and accomplishments of each systems application area is given and

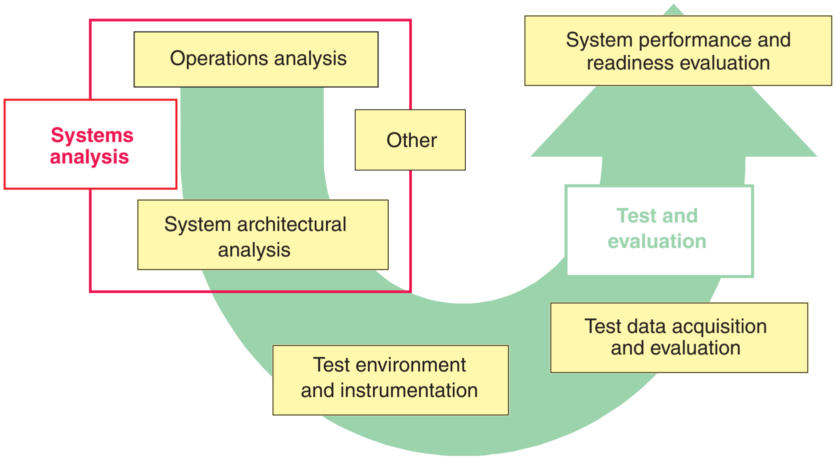

Figure 1. Functional taxonomy of SA/T&E.

then used to reference succeeding, more detailed discussions of SA/T&E. A summary of APL's overall SA/T&E strengths, weaknesses, and standing in the community is given, followed by a discussion of critical challenges for the future of this work at the Laboratory.

HISTORY, PROGRAMS, AND ACCOMPLISHMENTS

Highlights of the history, programs, and accomplishments in SA/T&E at APL are presented in Fig. 2. Each bar shows the systems application area followed by the major programs within that area. The significant S&T accomplishments are identified as triangles above each bar. Nine major areas of systems application are listed and are the basis for the more detailed descriptions to follow.

Significant S&T accomplishments in systems analysis center around the development of system simulations that are used in operations and architectural analysis as well as in detailed design and test evaluations. The evolution of these techniques, coupled with the progressive development of seminar war-gaming methods, has led to special Warfare Analysis Laboratory Exercises (WALEXs)[1] used in operations analysis. The systems engineering approach, developed in the early years for missile engineering,[2] became part of the culture throughout the Laboratory and was

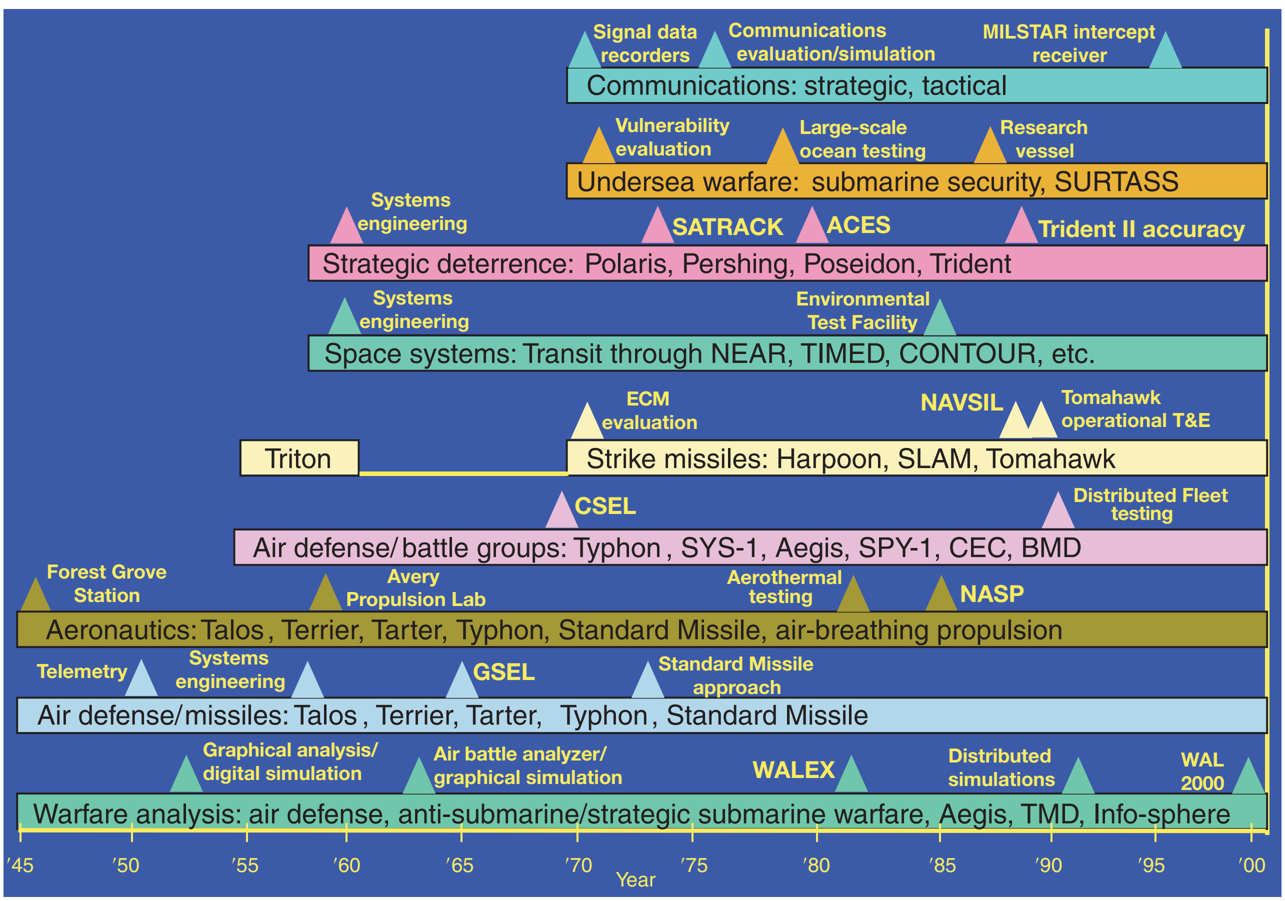

Figure 2. The history, programs, and accomplishments in SA/T&E at APL.

uniquely adapted for space systems development and strategic deterrence T&E.

Significant S&T accomplishments in T&E center around the development of detailed digital and hardware-in-the-loop (HIL) simulations for test data validation, special test facilities like the Avery Advanced Technology Development Laboratory (AATDL) for advanced development, and special space systems test facilities like the Environmental Test Facility. At-sea "hands-on" testing in the Fleet has yielded valuable insights into operational environments and system performance. In some cases, special analytical evaluation tools and instrumentation like those developed for Trident II accuracy were needed to meet evaluation requirements.

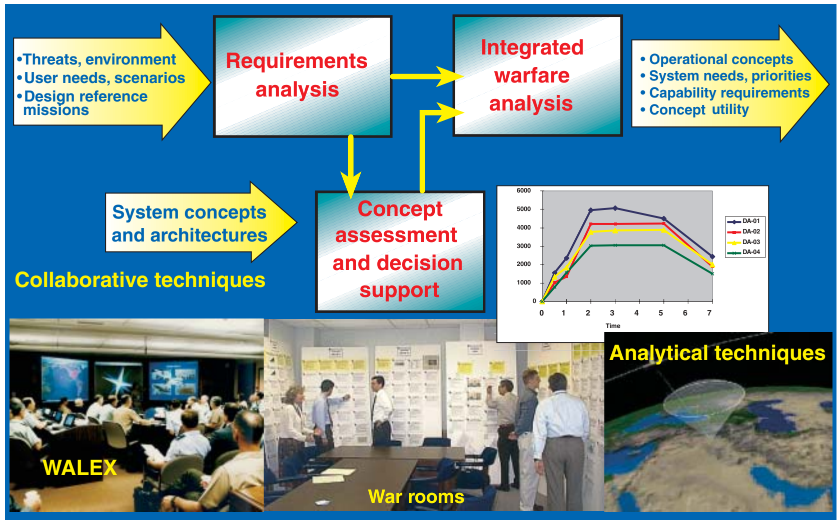

Figure 3. Elements of warfare analysis.

SYSTEMS ANALYSIS AT APL

In the broad sense, systems analyses are pervasive in every department of the Laboratory. In the more narrow sense, as defined above (i.e., operations and architectural analyses), most of APL's systems analysis expertise is concentrated in warfare analysis, air defense, space systems, and strike systems. Operations analysis determines what operations need to be performed by the system. It evaluates mission objectives, the threat, the environment, design reference missions, and concepts of operations and determines system functional and performance requirements, design constraints, and system utility. Architectural analysis determines the structure (e.g., building blocks) of the system. It involves subsystem functional and design trade-off analyses and defines interface specifications and performance requirements. Operations and architectural analyses can be carried out at the campaign level, system-of-systems (SoS) level (e.g., combat system), and individual systems level (e.g., missile, radar). In this context, warfare analysis is mostly carried out at the campaign level, with operations analysis and some higher-level architectural analysis. Air defense, strike systems, and space systems involve both operations and architectural analysis, but at the SoS and systems level.

Warfare Analysis

Warfare analysis is the largest concentration of systems analysis at the Laboratory. It analyzes the requirements and effectiveness of Joint warfighting systems and forces (Fig. 3). The analysis of user and mission requirements across the Joint warfighting spectrum is the first step, as APL sponsors and warfighters participate in the development of requirements elicitation sessions such as WALEXs. These collaborative sessions focus on future threats facing the warfighter, operational needs analysis and capture, Joint warfare requirements development, and interoperability need identification. System concepts and system architectures are then developed and evaluated, either through rigorous trade studies, sensitivity analysis, and risk assessment tasks, or through more formal analysis-of-alternative studies. These concepts and corresponding analyses are then brought again to the sponsors and warfighters. Through visualization techniques and decision-making methods and toolsets, the sponsors and warfighters then collaboratively assess the concepts in the context of requirements, Joint military tactics and operational concepts, and cost and schedule constraints. Systems analysis is also required to integrate the evaluation of system concepts and architectures across mission areas (strike and air defense, for example) or within a multimission Joint Task Force.

The application of S&T to this type of systems analysis primarily involves the modeling and simulation of system performance and operations. Mathematical modeling and computer simulation are also required for the evaluation of concepts and architecture alternatives. Decision support techniques and tools aid in the assessment of systems in Joint warfare analysis, including state-of-the-art collaborative techniques and operations research.

Air Defense/Battle Groups and Missiles

Systems analysis activities in air defense/battle groups tend to emphasize both operations analysis and architectural analysis at the SoS (combat systems) level, starting with the need and requirements definition and progressing through concept formulation, analysis of alternatives, and risk reduction. The SoS is designed through a series of trade-offs using simulations and visualization tools. Examples of these tools are found in the new System Concept Development Laboratory, which features the automated visualization of large-scale system diagrams for an entire battle force with links to many other databases, simulations, and system equipments.

Although models and simulations of every important system within the combat system are used at varying levels of fidelity in battle group systems analysis, a special concentration at the missile level is used for missile analyses. The Area/Theater Engagement Missile/Ship Simulation (ARTEMIS)[3] is an example of a detailed, integrated simulation of the entire Standard Missile kill chain, from target detection to intercept. The Advanced Missile System Evaluation Laboratory (AMSEL) contains all the variants of the Standard Missile six-degree-of-freedom (6-DOF) digital simulations for architectural analysis.

Strike Systems

Systems analysis for strike systems is similar to air defense, but more in terms of offensive power projection systems, with a focus on aircraft and cruise missiles. Most of the systems analysis is at the SoS level (ship-based power projection; command, control, communications, computers, intelligence reconnaissance, and surveillance) and system level (cruise missiles, platforms, unmanned air vehicles), with campaign-level analyses performed by the warfare analysis area. System models such as missile engagement and force-level simulations, radar models, and communications models provide support to facilities such as the AMSEL.

Space Systems

The nature of space missions is usually quite different from the war operations evaluated in the previous discussions and much less legacy-oriented. Operations analysis includes mission objectives determination and concept formulation while keeping in mind the available technology capabilities and satisfying the mission constraints. "Brainstorming" is one of the techniques used in this phase of concept formulation. Simulation models are used to evaluate promising concepts. Once the top-level mission design concept has been synthesized, analyzed, and validated, the architecture analysis commences with subsystem definition and requirements for the launch vehicle, spacecraft, instruments, and mission operations. A close coupling between the science objectives and the resulting engineering to accomplish the mission is required to develop "better, faster, cheaper" spacecraft. A very structured design review process is used to ensure the success of all aspects of the mission.

TEST AND EVALUATION AT APL

Test and evaluation is pervasive throughout the Laboratory because of the hands-on systems engineering culture and our primary mission of solving "critical challenges" with "critical contributions." The contributions usually take the form of some system innovation that must be thoroughly tested for confident performance prediction. In some cases, the importance of the system and mission will demand a very rigorous and quantitative evaluation (e.g., strategic deterrence), while others will demand less. The following discussion first summarizes the generic steps in the T&E process that are usually followed (to one degree or the other) in most T&E programs at APL. A broad summary of significant T&E activities throughout the Laboratory is then presented.

Systems Engineering Approach

The systems engineering approach to T&E is shown in Fig. 4. This was extrapolated from experience with previous weapons systems T&E and especially that of Trident II. The left side illustrates the planning steps required to properly design an overall test program to provide adequate evaluation capability at certain milestones in the test program. The right side describes the execution steps in the T&E process. This process can be rather elaborate, as was the case for Trident, or simpler, as it is for nonstrategic systems, depending on the system type, stage in the acquisition process, and APL's role.

The key starting point in the systems engineering approach is specifying the top-level performance evaluation requirements (not how well the weapon system should perform, but how well we should know its performance, i.e., how confident are we in our performance

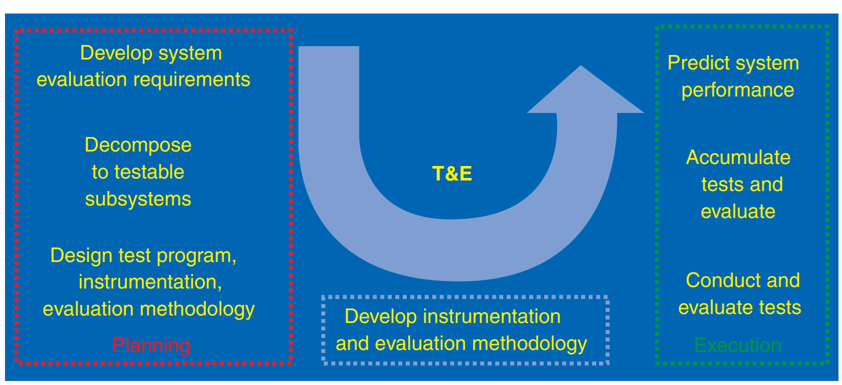

Figure 4. The systems engineering approach to T&E at APL.

prediction). A few test successes do not guarantee that the system will meet its objectives; they only show that success is possible. If there are no top-level measures-of-effectiveness (MOEs) evaluation requirements in terms of confidence, then one can be developed. This would be an iterative process among the developer, evaluator, and user.

The next step is to determine a complete set of lower-level measures of performance (MOPs) with associated confidence requirements over a reference set of scenarios needed to achieve the required MOEs and confidence bound. Testable MOPs (or ones that are extrapolated from tests) are sampled from distributions commensurate with assumed confidence bounds, and *scenario simulations* are used to calculate the resulting MOEs (and confidence bounds). This process is iterated until an optimized set of MOPs (and confidence bounds) is achieved. A possible optimization strategy might be to "balance" each MOP confidence contribution to MOE confidence. Other strategies might reflect the difficulty (e.g., cost) in achieving certain MOP confidence bounds such as reliability. Many trade-offs could be evaluated.

A test program and an analysis methodology are then designed to meet each MOP confidence requirement by hypothesizing various feasible tests (system, subsystem, component), test sizes, instrumentation quality, and evaluation methodologies. Appropriate simulation models (covariance or Monte Carlo) are used to evaluate each hypothesized set until an optimized set is obtained. The results of this phase might necessitate a return to the previous phase to revise the required MOP confidence bounds.

Such a process provides for trade-offs to be made while quantifying the implications of decisions to test more (or less), to instrument different functions or systems, or to change the quality of the instruments. As defense spending and costs associated with system development and T&E come under increasing scrutiny, it becomes even more important to be able to quantify the relative benefits of test size and instrumentation quality. Quantifying the confidence with which we will know system performance provides a metric by which we can assess the value of our test programs, instrumentation, and analysis approaches.

As for the execution steps in the T&E process (Fig. 4, right), tests are conducted by traditional testers and evaluators, but with the evaluation outputs complying with the system evaluator's requirements. Test types include system, component, or subsystem tests; monitoring of an in-place system as it awaits operational usage; and subsystem tests "in the loop" of a simulation. Per-test fault detection/isolation can be conducted by traditional tester/evaluators, but with results validated by the system evaluator. Isolated faults can be fixed by the developer and removed from the database and models.

The system evaluator calculates a cumulative update of the MOP models, confidence intervals, and estimated distributions. Where possible, physics-based models that fit data (system identification) from diverse tests are used to gain maximum information from each test. If the model can be broken down to a set of parameters that are independent of the scenario, then statistical leverage can be gained by accumulating across all relevant but disparate tests.[4] The associated uncertainty (confidence bound) in the model estimates can be calculated from the known observability, instrumentation quality, and number of tests. Prior information from development testing can also be used initially until an adequate number of postdeployment tests can be accumulated. Periodic reassessment of the test program's adequacy to estimate the MOPs and associated confidences may require a return to the planning stages to reassess the confidence requirements.

Next, the system evaluator predicts the MOEs and confidence bounds for the required reference set of scenarios using the force-level simulations to flow up the MOPs (and confidence bounds) to the MOEs (and confidence bounds). Model fault isolation is conducted to determine which MOP is out of specification and then to determine what that MOP's resultant contribution is to the MOEs. Periodic reassessment of the test program adequacy for current MOE requirements must be done.

Finally, the system evaluator conducts force-level evaluations with the latest estimated models by using force-level simulations to flow up the estimated MOPs (and confidence bounds) to the MOEs (and confidence bounds) to evaluate the adequacy of the systems for many different campaigns. This allows trade-offs to be made for optimum planning of the force-level deployment such as in ballistic missile defense (BMD).[5] A functionalized performance prediction model can also be developed and updated to be used in the real-time employment of the weapon system against an operational threat.

Strategic Deterrence

Because of the national importance of our strategic deterrent systems, APL instituted a T&E program of the highest caliber beginning in the late 1950s for the Navy's Fleet Ballistic Missile (FBM) Strategic Weapon System, an effort sponsored by Strategic Systems Programs (SSP). The submarine-launched ballistic missile (SLBM) on its nuclear-powered submarine platform provides a mobile, long-patrol duration, covert, and invulnerable strategic deterrent force. Figure 5 depicts the three major types of SLBM system testing: (1) demonstration and shakedown operations (DASOs), i.e., flight testing conducted before deployment after either new submarine construction or a shipyard overhaul period; (2) patrol, i.e., recurring nonflight tests conducted during each strategic deterrent patrol; and

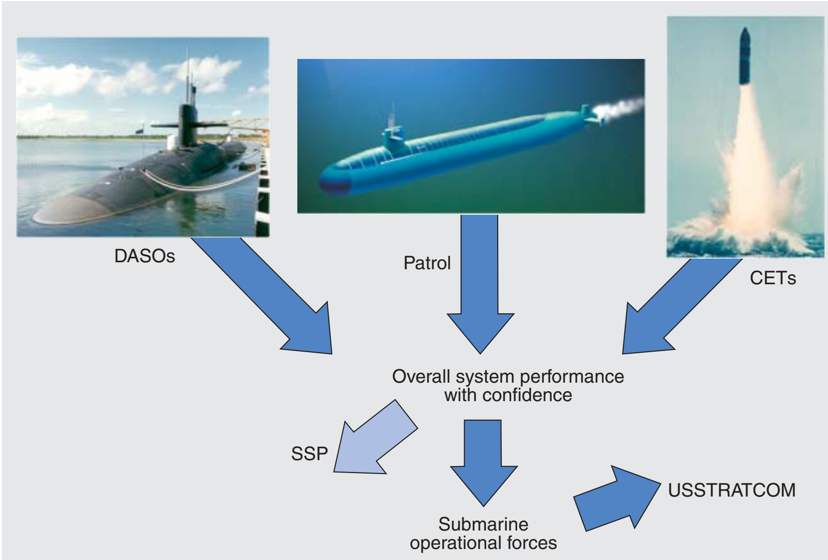

Figure 5. Strategic deterrence systems T&E.

(3) Commander-in-Chief evaluation tests (CETs) or follow-on CETs, i.e., end-to-end weapon system tests, including missile flights conducted periodically throughout the life of the system with randomly selected missiles. The results of the evaluations are provided directly to the Atlantic and Pacific Fleet Commands, which then present them to the U.S. Strategic Command (USSTRATCOM) for strategic targeting requirements. In this way APL's T&E activity is considered "independent" of the developer, SSP.

The scope of these ongoing evaluations represents the largest concentration of T&E expertise at the Laboratory. SLBM T&E was developed using the full scope of the systems engineering approach described previously. The major S&T innovations in this area—SATRACK, the Accuracy Evaluation System (ACES), and Trident II accuracy (Fig. 2)—are detailed next.

SATRACK, developed in the late 1970s, uses Global Positioning System (GPS) satellites to precisely track Trident missiles from DASO and CET tests. It is illustrated as the powered flight portion of the instrumentation in Fig. 6. The GPS radiates to the test missile containing a GPS translator (instead of a receiver), which relays the raw navigation signals to land- and sea-based receiving stations for wideband recording. The recordings are tracked/corrected following the test at the APL SATRACK facility and processed in a large Kalman filter along with missile telemetry for estimation of individual guidance system errors. These estimates can then be propagated to the target point to explain the observed test miss.

Since Trident II was to have a more stringent accuracy requirement, the ACES study used the systems engineering approach to develop system evaluation requirements in terms of accuracy confidence. Instrumentation, test programs, and processing methodology were then determined to satisfy the confidence requirements, resulting in the instrumentation suite shown in Fig. 6. Flight testing then featured an improved SATRACK system for powered flight, inertial instrumentation for deployment and reentry, and improved underwater navigation instrumentation for the prelaunch phase. The major new addition from the ACES study was the cumulative model estimation with confidence, where the per-test results from each test are accumulated via a maximum likelihood method as shown in Fig. 7. Here, a physics-based model of the system—where the unknown parameters are fundamental errors (e.g., gyro drifts) common across all tests—is fit to all the data (even though the test scenarios are different) to estimate the underlying system model and the associated confidence. This results in an estimated model (vs. a validated model) that is capable of predicting accuracy performance to untested conditions with quantified confidence. The new accuracy modeling, coupled with traditional reliability modeling, enabled Trident II performance to be predicted with quantified confidence. Starting with Trident I in the late 1970s, over 180 flights have been processed by SATRACK, with about 100 being Trident II.

Strike Systems

The Laboratory provides two activities in the T&E of strike missiles as TDA for the sponsor, PEO(W), Cruise Missiles and Unmanned Aviation. The first activity consists of testing concepts and hardware in missile system development and conducting fault isolation and risk mitigation in flight test analyses when needed. Missile 6-DOF flight simulations and a number of testing/simulation facilities are employed. The Mission Planning and Development Laboratory is used to evaluate terrain and optical cruise missile navigation. The Guidance System Evaluation Laboratory (GSEL) is employed to test missile interfaces and guidance/navigation. This is a real-time, multiple-guiance mode, dual-chamber (RF/IR), HIL simulation for end-to-end evaluation of the missile operation. The Navigation and Guidance System Integration Laboratory is used to conduct real-time testing of actual missile GPS and inertial navigation hardware under simulated, realistic dynamic conditions. It has been employed in conjunction with the SATRACK facility to test GPS anti-jam concepts. The Antenna Range

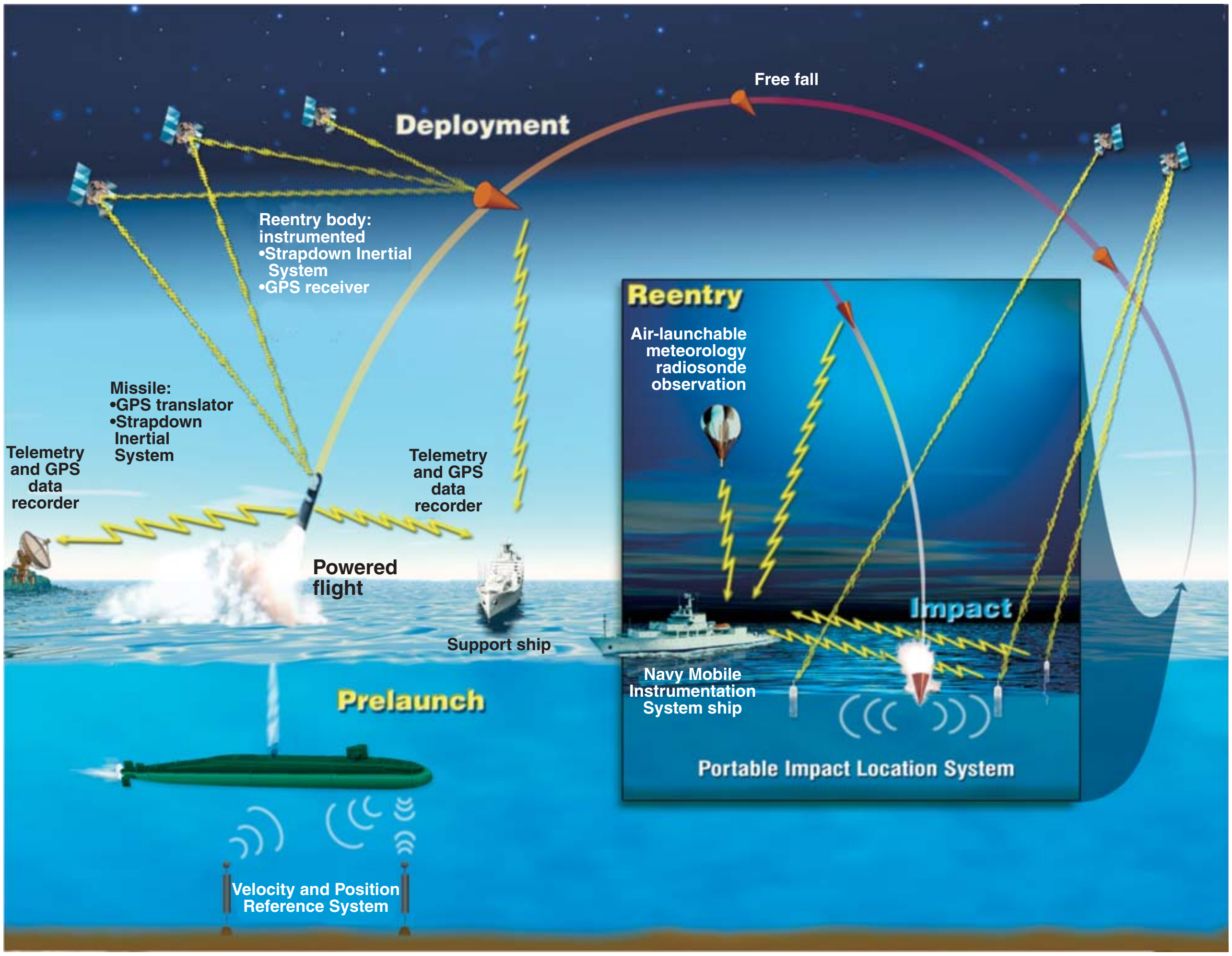

Figure 6. The Trident II instrumentation suite.

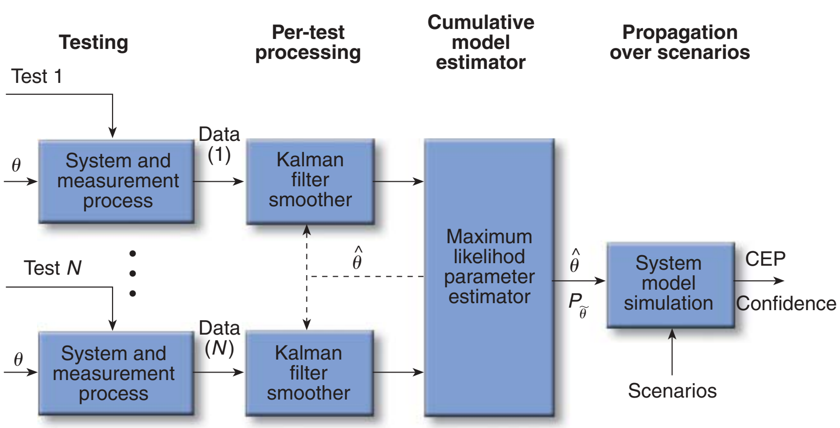

Figure 7. Model estimation for Trident II resulting in credible performance prediction of a system critical to the U.S. government and military. (θ=true model parameter vector, $\hat{\theta}$ = estimate of θ, $P_{\tilde{\theta}}$ =covariance of estimation error in θ.)

and Boresight Test facility is used to evaluate antenna systems and the angle accuracies of tracking systems.

The second T&E activity is the planning, coordination, and evaluation of all Tomahawk cruise missile flight testing, from development through the postdeployment acquisition stages. The approach is similar to but a more simplified version of the Trident evaluations. Using impact and flight test instrumentation, the target miss is partitioned into the major subsystem contributors, enabling cumulative accuracy analysis with confidence across all tests. Performance prediction with confidence over nontested scenarios can also be done with this approach.

Air Defense/Missiles

For the T&E of air defense/missiles (Fig. 8), the Laboratory, in its TDA role for Standard Missile, conducts testing of concepts and missile hardware and software. This is accomplished using the GSEL and end-to-end 6-DOF engagement simulations during missile

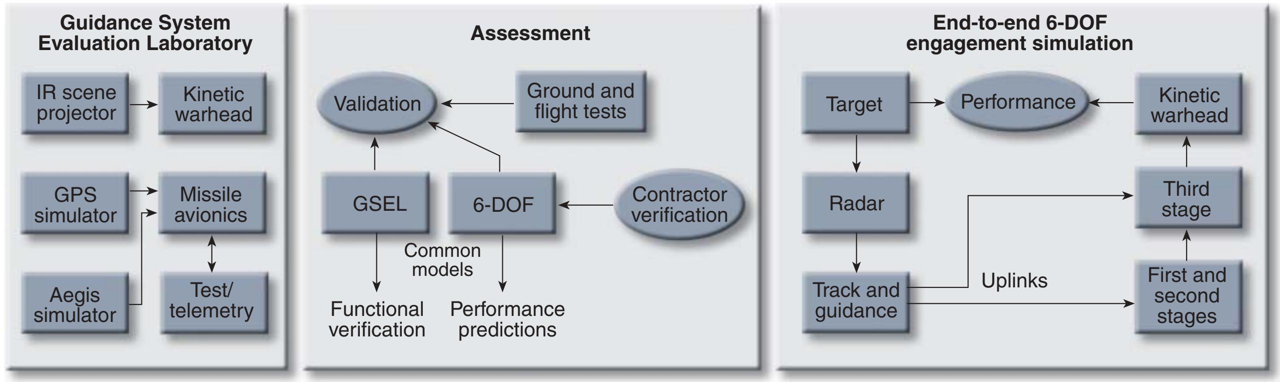

Figure 8. Air defense/missiles T&E.

development. The T&E in this area also provides independent development flight test support. Pretest flight test support consists of risk reduction, performance prediction, and flight test planning and design. Posttest activities are flight assessment, performance validation, and adjustment of models. The GSEL provides HIL testing, exercises real system components and computer programs, and assesses real-time processing issues. The 6-DOF simulations provide high-fidelity digital simulation, more completely represent complex flight environments and system interactions, include statistical variations, and evaluate algorithms. Both the GSEL and the 6-DOF simulations are used to validate flight test results, which are then compared to the results from the development contractor. The primary S&T is conducted in the GSEL and 6-DOF simulations. Another significant testing activity in the development of missile aerodynamics and propulsion technology is conducted in the AATDL, to be discussed later.

Air Defense/Battle Groups

The character of the air defense T&E for battle groups differs from its T&E role in missiles. Here the activities are wide ranging, from testing of individual combat system elements to battle group/theater-wide command and control systems. The approach includes planning, implementation, and instrumentation for critical experiments; data retrieval; Fleet exercises; and development tests for risk reduction, performance, and service life assessments. Two major types of activities occur: (1) use of Laboratory facilities for test planning, rapid prototyping, and testing of advanced concepts, and (2) use of field exercises for operational performance evaluations. An example of the former is the Combat Systems Evaluation Laboratory (CSEL), a major facility for development testing of advanced system concepts and prototypes. CSEL is a collection of military and commercial equipment and computers configured to support realistic evaluations of combat information center functions, advanced display systems, radar system processing, communication improvements, and distributed command and control systems. It has been used in most of the battle group programs such as Aegis, AN/SPY-1 radar, Cooperative Engagement Capability (CEC), Area Air Defense Commander, and many others.

An example of large-scale field exercises was the distributed combat system T&E from development (1990) through operational evaluation (2000) for the CEC system. This series of Fleet exercises featured a separate evaluation network with a mobile command station of CEC displays and communications for real-time coordination and integration. The challenge was to separate out the CEC functions from other combat system functions in the scenario design and data analysis. Also, the evolutionary changes in the CEC and other combat systems over the 10-year testing period had to be accommodated. The primary S&T was in Laboratory facilities such as CSEL and the real-time coordination/integration/display of the wide-area Fleet exercises.

Aeronautics

The AATDL is a comprehensive research facility that performs T&E on a broad range of technologies related to submarine operation, space systems, air defense, and strike systems. Examples are internal and external aerodynamics evaluation, aerothermal/aero-optical sensor testing, development of target vehicles for simulated ballistic missile intercepts, and development of an arc-fault detection system to provide protection in electrical switching cabinets on Navy nuclear submarines. The AATDL has enabled the successful development of guided missile aerothermodynamics and propulsion technology for air defense/missile systems. It has the resources and staff to conduct experimental work and testing of advanced systems—from conceptual design through engineering development—involving instrumentation, controls, high-speed data acquisition, combustion, fluid dynamics, heat transfer, energy conversion, power distribution, and mechanical structures.

Communications

Two distinct areas of communication systems T&E are performed at the Laboratory: strategic and tactical. Strategic communications T&E, shown in Fig. 9, features continuing evaluation of SSBN and Intercontinental Ballistic Missile (ICBM) connectivity in terms of survivability, availability, reliability, and timeliness. Figure 9b refers to work done with a massive Monte Carlo simulation that has been developed from analysis of the test data to predict the performance of strategic communications links in jamming and nuclear environments, where no test data are available. This has resulted in improved communications performance, equipment, and concepts of operations. The primary S&T consists of validation of very-low-frequency propagation and noise models, invention of the operational nonlinear adaptive processor developed in the Experimental Communications Laboratory, and development of wideband recorder technology.

Tactical communications T&E is part of APL's TDA role in larger projects. For instance, for the Tactical Tomahawk program, ultra-high-frequency SATCOM connectivity is currently in engineering testing. The Multifunction Buoyant Cable Array features testing of a towed array for submarine connectivity at speed and depth. Prototype testing of SATCOM connectivity for CEC range extension is also ongoing. These are S&T efforts in innovative special-purpose instrumentation, automation tools, and on-site communications.

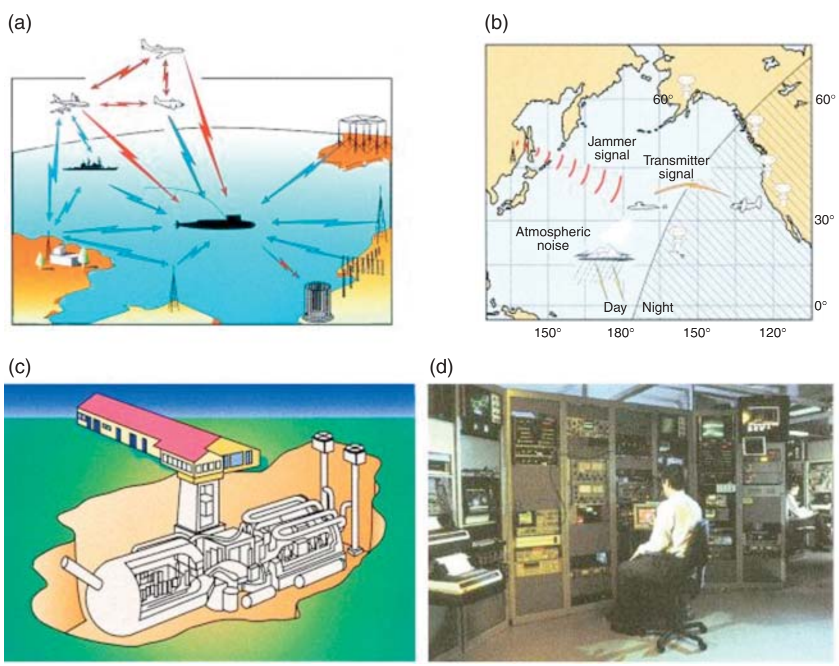

Figure 9. Strategic communications systems T&E: (a) FBM communications evaluation, (b) strategic communications simulation predictions, (c) ICBM communications evaluation, and (d) Experimental Communications Laboratory.

Undersea Warfare

Two major areas of T&E in undersea warfare are to (1) study the detectability of our SSBNs and test the resulting developed countermeasures, and (2) study the detectability of enemy submarines and develop acoustic surveillance systems. As illustrated in Fig. 10a, the SSBN Security Program regularly conducts large-scale, at-sea measurement efforts involving air platforms, surface ships, and submarines. These tests are designed to collect detailed information about the ocean environment and potentially detectable submarine signatures. The charter of the program is to assess the potential threats to the U.S. SSBN force from all possible submarine detection methodologies and to develop countermeasures when required. A typical multi-year project within this program would begin with preliminary analytical and computer modeling of the detection mechanism. If the models predicted any meaningful performance, only then would the design and fabrication of test hardware follow, and one or more at-sea exercises to collect ground-truth data would be conducted. The instrumentation deployed during these tests usually pushes the state of the art in sensing and processing. Past efforts have addressed a wide range of submarine detection approaches, including a variety of acoustic and nonacoustic technologies. This program has assured the safety of the SSBN Fleet for over 30 years.

The second T&E activity in undersea warfare is part of the development of undersea acoustic surveillance systems to detect enemy submarines. The major work is in investigating the use of low-frequency active acoustics using an at-sea anti-submarine warfare research vessel, specifically outfitted under the Laboratory's direction. The primary program was to develop the Surveillance Towed Acoustic Sensor System/Low Frequency Active. The S&T was similar in kind to the SSBN Security Program but included the specially outfitted research vessel.

Space Systems

Space systems T&E is necessarily different from the efforts described so far. Here, the Laboratory develops and builds an operational, one-of-a-kind (usually) system that must work the first time in orbit. Testing starts at the subsystem "bench level" with functional tests for proper interfacing to the external environment; performance testing under dynamic

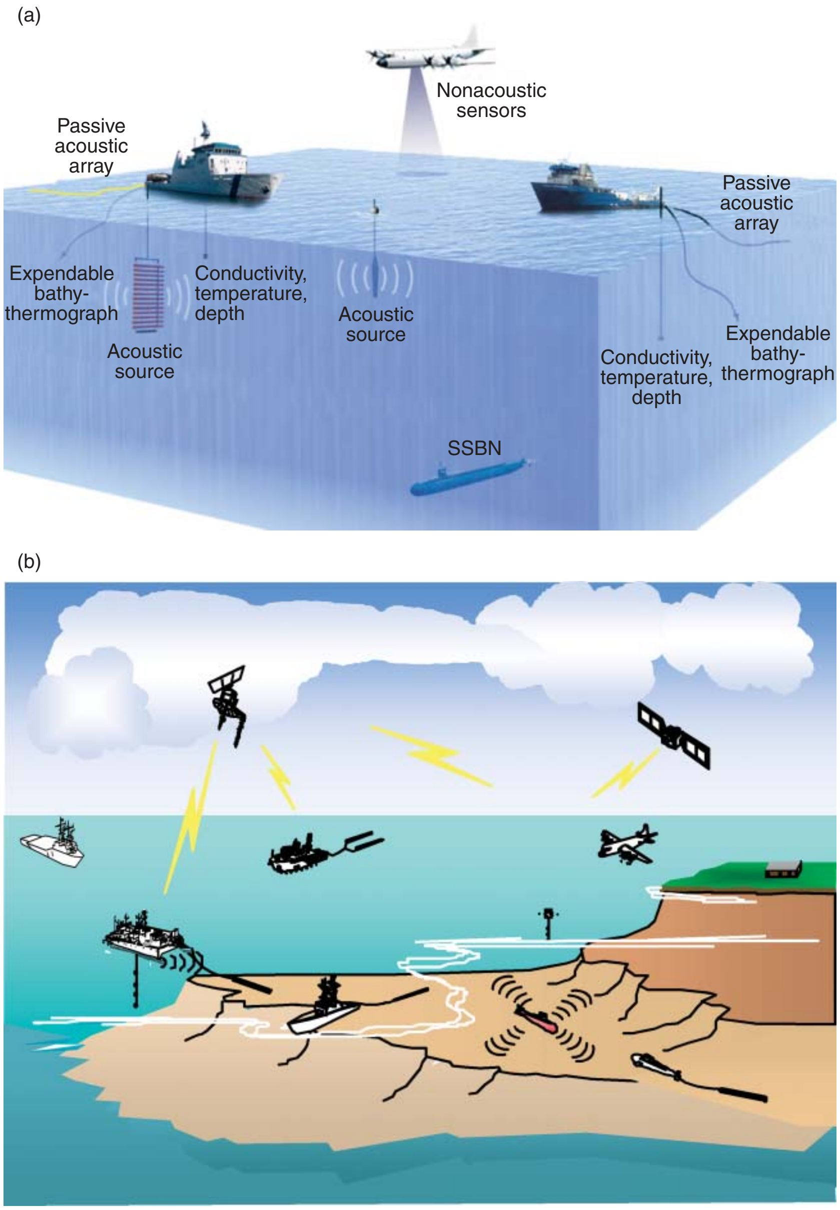

Figure 10. Undersea T&E: (a) Submarine Security Program to study the detectability of SSBNs and (b) undersea sensors to study the detectability of enemy submarines.

simulations of orbit, attitude, and power; and environmental tests in vibration and thermal vacuum. The next step is at the full-up spacecraft level with all instruments for functional, performance (mission simulations), and environmental (acoustic, vibration, mechanical shock, thermal vacuum and mass properties) testing. Much of this testing is performed in the Environmental Test Facility, which provides laboratories, instrumentation, and data acquisition capabilities for thorough thermal, vacuum, and dynamic testing of flight hardware at all levels of assembly. Launch-site testing repeats the functional and performance tests. Postlaunch testing features early on-orbit checkout to verify routine performance, guidance and control ("walk before you run"), special tests to verify performance of nonroutine operations, and redundancy checkout. The S&T in these T&E activities has been in the Environmental Test Facility and in the progressive automation of the test equipment and procedures for more efficient and comprehensive evaluations. Examples are improved spacecraft built-in testability, automated Ethernet ground systems connections, use of the APL Communications Language, automated testing of spacecraft autonomy rules and command sequences, the Mini-Missions Operations Center, and decoupled instrument and remote testing.

STRENGTHS AND COMMUNITY STANDING

The SA/T&E area at APL has a number of unique strengths. Warfare analysis is well regarded for developing and using leading-edge technology in collaborative analysis among heterogeneous organizations and for mission-level modeling and simulation of combat systems. APL's air defense SA/T&E expertise is based on an unparalleled legacy of guided missile system and battle group engineering, development, and testing; the Laboratory is one of the premier centers of excellence in BMD. APL's strategic deterrence T&E capabilities have enabled the development of unique confidence-based evaluations for system performance assurance by using innovative GPS instrumentation and processing and modeling techniques. This capability is necessarily complex and expensive. Aeronautics T&E activity has resulted in the development of a center of excellence in guided missile aerodynamics and propulsion experience and is well regarded for its role in guided missile development. Strike missiles T&E has led to the development of unique facilities for testing GPS concepts. APL's efforts in communications T&E have made the Laboratory a recognized leader in SLBM and ICBM communications testing and extremely-high-frequency testing. Undersea warfare T&E capabilities show strengths in sensor development, at-sea and algorithm testing, and vulnerability analysis. Space systems T&E work is well regarded by our sponsors for producing highly reliable and durable systems for space exploration.

In general, the strengths of the SA/T&E area derive from our test facilities and simulations, our hands-on operational experience with the systems we are developing, and, in some cases, our unique instrumentation developments. A significant reason for these strengths has been our requirements-driven systems engineering approach, the hallmark of most APL programs. In some cases, this has resulted in confidence-based T&E. Externally, we are well regarded in our separate communities for our strengths and accomplishments. Finally, the Laboratory is known as one of the centers of excellence in space exploration and BMD.

CHALLENGES FOR THE FUTURE

SA/T&E at APL will continue to be a necessarily strong component of our future programs. A challenge for APL is to improve cross-fertilization of its T&E technologies beween the strategic and tactical communities. The challenge for warfare analysis will be in applying advanced systems analysis techniques to sponsor problems in areas of operations research (optimization and network analysis), decision seminars, interactive war-gaming, and information integration (mission-level information into higher levels). Aeronautics T&E efforts, with their extensive S&T and experience, should "extend their reach" beyond being a T&E service to other departments. Strike missile T&E should embed a test-GPS capability within the Tactical Tomahawk missile. Undersea warfare T&E faces new challenges in shallow water operations and low-frequency active acoustics countermeasure testing.

Air defense will be challenged by Fleet and homeland defense against cruise and ballistic missiles. Limited defense budgets and concern for collateral damage will add new constraints. The importance of defending against ballistic missiles with strategic warheads (nuclear and chemical/biological) will require credibility (confidence) in BMD performance on the same scale as for our Trident SLBM. This will require a paradigm shift in the T&E approach to provide quantified confidence in performance assessments. An independent SoS evaluator will be needed to span all areas of T&E. Maximum information from all types of testing will be needed because of the restrictions of limited system testing and budgets.

Strategic deterrence systems will be increasingly sea-based with required life extensions. New SLBM missions are being considered such as global flexible-response precision strike with low collateral damage. Budget constraints will limit traditional flight testing, requiring new reliability evaluation techniques and other new testing and instrumentation approaches.

SUMMARY

There are many SA/T&E centers of activity throughout the Laboratory. The systems analysis activities are scattered over about five centers in warfare analysis, air defense/missiles, air defense/battle groups, strike missiles, and space systems. Our strengths in this area are in our system simulations and war-gaming seminars. The T&E activities are distributed over about eight centers of activity in strategic deterrence, strike missiles, air defense/missiles, air defense/battle groups, aeronautics, communications, undersea warfare, and space systems. Our strengths in this area are in our digital and HIL simulations, many test facilities, unique instrumentation and, in some cases, the Laboratory's unique evaluation tools. Both areas are steeped in our systems engineering and operationally experienced cultures.

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THE AUTHOR

LARRY J. LEVY is Chief Scientist of the APL Strategic Systems Department. He received his Ph.D. in electrical engineering from Iowa State University in 1971, specializing in control theory. Dr. Levy has worked in the areas of navigation system development and system test and evaluation. He has over 35 years of experience in Kalman filtering and system identification and is the author of numerous papers and presentations on these subjects. Dr. Levy was the co-developer of the GPS translator concept in SATRACK (a GPS-based missile tracking instrumentation system) and was instrumental in developing the end-to-end methodology for the Trident II accuracy evaluation. He teaches graduate courses in Kalman filtering and system identification at The Johns Hopkins University Whiting School of Engineering and also teaches these subjects for Navtech seminars. His e-mail address is larry.levy@jhuapl.edu.