



# Vehicle Technology at APL

*John J. Wozniak*

Vehicle technology at APL encompasses the four disciplines of guidance and control, navigation, aerodynamics/hydrodynamics, and propulsion as applied to military platforms and spacecraft. These disciplines are addressed in terms of historical background at APL, the status of current work, and examples of important new initiatives. The information was compiled for the Senior Leadership Team’s “Vehicle Technology” session. The Laboratory has developed a unique suite of computational, data processing, hardware-in-the-loop, and test facilities for vehicle technology; when coupled with the expertise of our staff, these assets have enabled APL to make important contributions to our sponsors.

## INTRODUCTION

This article is drawn from the Senior Leadership Team presentation on the topic of vehicle technology as practiced at the Laboratory. In the context of this article, “vehicle” refers to military platforms and spacecraft that transport or deliver sensors, transmitters, or weapons from a launch location to a target location or an orbit. The list encompasses tactical and strategic missiles, surface ships and submarines, Earth-orbiting satellites and interplanetary spacecraft, unmanned aerial and undersea vehicles, “smart” bombs, and airdropped sensors.

The Laboratory’s involvement in vehicle technology can be traced to the end of World War II when the Navy asked APL to lead the Bumblebee Project in developing a long-range, supersonic, ramjet-powered guided missile to defend the Fleet. APL undertook the needed aerodynamic, propulsion, guidance and control (G&C), and airframe research to evolve the then-fledgling technology of guided missiles. Through innovation, science, and sound engineering, the Laboratory,

along with government agencies and industry, developed the highly successful Talos missile that is still used by the Navy as a target missile.

The three key disciplines—G&C, aerodynamics/hydrodynamics, and propulsion—were supplemented with navigation in the mid-1950s when APL accepted the mission to support the Navy’s submarine-launched Polaris strategic missiles by developing the Transit satellite navigation system.

APL is a problem-solving organization, and our main strength is systems engineering. This is especially true for complex vehicle systems. In some instances, we may conduct applied research to explore a more basic aspect of vehicle technology (e.g., drag reduction), but most of our vehicle technology work is applied engineering to help develop a new weapon system or spacecraft or to assess or improve the operation of an existing system.

In this article we hope to convey, in general terms, the work that we do in the broad category of vehicle technology. This description will encompass a brief

history of each discipline, the status of the work, and current strengths, along with some examples of technologies that were presented during the Senior Leadership Team poster session. Figure 1 illustrates a taxonomy of vehicle technology at the Laboratory. Under each of the four disciplines is a list of the work areas in which we are currently engaged to various degrees of involvement.

## NAVIGATION

### Historic Highlights

Navigation is the process of determining vehicle position, velocity, and (sometimes) attitude in absolute or relative terms. As early as the 1950s, when the Laboratory was investigating long-range supersonic cruise missiles as strategic weapons, the importance of this highly technical and challenging technology was recognized. Throughout the past 50 years, APL has made numerous navigation contributions that enable weapons to successfully engage targets.

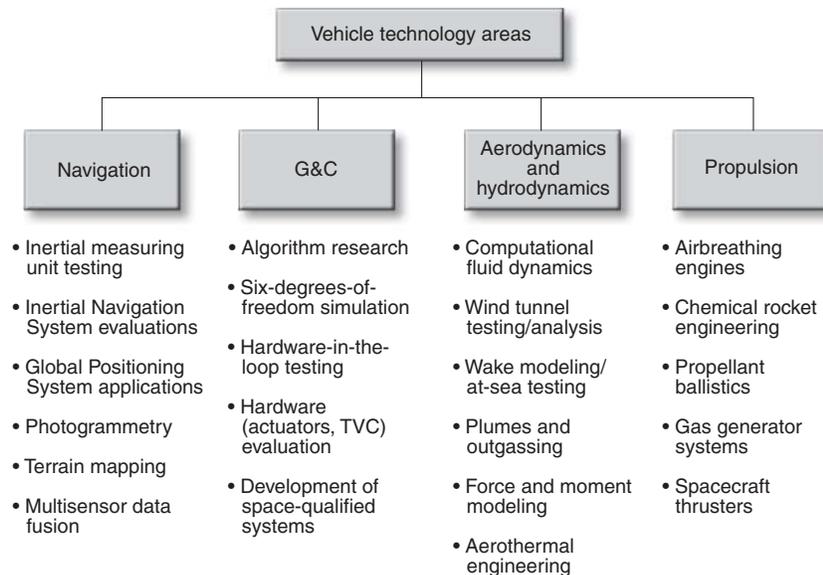
In the early 1950s, the need for strategic deterrence was recognized, and both ballistic missiles and supersonic cruise missiles were investigated. The Laboratory conducted a research effort for a long-range cruise missile that became known as Triton. The project emphasized the importance of accurate delivery to minimize nuclear warhead size and collateral damage. Navigation hardware at the time did not support accurate delivery, and many techniques were investigated to update the missile's navigation system in flight. A map-matcher concept seemed most applicable. APL engineers recognized that the problem of tracing inertial system drifts differed little from tracking a maneuvering target; thus previous work was brought to bear, and a "correction

computer" was used to apply map-matcher results to the inertial navigator. The methods used in the correction computer were generalized and extended by Richard S. Bucy, who had worked at APL, and R. E. Kalman to develop what is now known as the Kalman filter, which is central to all navigation systems today.

In the late 1950s, the Laboratory was assisting the Navy in developing the Polaris Fleet Ballistic Missile (FBM) Strategic Weapon System; however, a serious problem existed. To accurately deliver an unguided ballistic missile, the launch platform had to know both the target location and its own location. Accurate knowledge of position at sea was a difficult issue for which there was no solution, since all navigation equipment drifts with time. This navigation problem was, surprisingly, solved with the help of the Soviet Union's Sputnik satellite in 1957. APL scientists tracked the signal from Sputnik and realized that the satellite's orbital parameters could be determined from the Doppler shift.<sup>1</sup> Frank McClure made one of those breakthroughs that has often characterized APL work—he found that the process could be inverted to determine position on Earth. This insight was the genesis of Transit, the world's first satellite navigation system. Transit not only solved the problem of navigation at sea (at least when a satellite was in view), but this development led to the formation of the APL Space Department. The Transit system helped various platforms navigate at sea and on land until it was replaced by the Global Positioning System (GPS) in the late 1970s.

In helping the Navy develop the Polaris strategic missile, APL defined and conducted comprehensive tests to evaluate the system's reliability, accuracy, and performance. This included an independent technical evaluation of the FBM submarine's inertial navigation system; the Laboratory's Polaris Division (forerunner to the Strategic Systems Department [SSD]) established the Patrol Navigation Evaluation Group to provide the needed technical assessment.

In the mid-1970s, the Navy's Strategic Systems Program Office was tasked to improve the accuracy of the Trident I missiles. To support this goal, a new technique was needed to estimate the missile's guidance system error and reentry body impact accuracy. APL conceived of, and pioneered, the technology of post-processing two satellite GPS signals relayed from the flight test missile to precisely estimate the flight trajectory. SATRACK was begun in 1974 and,



**Figure 1.** Vehicle technology taxonomy depicting the four broad disciplines and types of work currently conducted at the Laboratory (TVC = thrust vector control).

over its 28-year history, has played an important role in establishing the accuracy of all FBM weapon systems.

In the early 1970s, the Navy initiated development of a subsonic, long-range strike cruise missile—Tomahawk. The missiles's long flight times required that navigation drift be corrected in flight. Low flight altitudes and weather precluded celestial updates, so the Laboratory helped pioneer the use of terrain matching. In-depth understanding of the Tomahawk problem enabled APL engineers to define the requirements for the TERCOM (TERrain COntour Matching) System and predict overall system operational performance.

With the introduction of a conventionally armed Tomahawk in the 1980s, higher accuracy was needed, and an optical Digital Scene Matching Area Correlator (DSMAC) System was devised. The Laboratory developed the algorithms that enabled prediction of the scene and employment conditions that would lead to high-confidence navigation updates.

Also in the early 1980s, the Space Department pioneered a space-qualified GPS receiver to provide for accurate onboard position, velocity, and orbit propagation. This engineering innovation led to the development of the GPS Navigation System (GNS), enabling development of satellites with advanced autonomy features and reduced mission operations costs. The first spacecraft to use this capability was Landsat-D, launched in July 1982.

In the 1990s, there was growing concern about the susceptibility of continuous GPS navigation to electronic countermeasures (ECM). To address these concerns, the Fleet Systems Department established the Navigation System Integration Laboratory (NAVSIL). NAVSIL's first use was to demonstrate that the Block III Tomahawk met its GPS jamming specification. It has since been used to test the ECM susceptibility of other weapons (e.g., Joint Direct Attack Munition [JDAM] and Block IV Tomahawk), to prototype innovative navigation system concepts (e.g., the Air Force Wide Area GPS Enhancement [WAGE]), and to support new navigation applications (e.g., initial vectoring for the Navy's exo-atmospheric ballistic missile defense [BMD] interceptor, Standard Missile-3 [SM-3]). The facility has undergone continued improvement to develop capabilities for hardware-in-the-loop (HIL) test and analysis of advanced weapons and support platforms.<sup>2</sup>

### Current Work and Important New Efforts

APL's navigation expertise provides a core contribution to tactical and strategic missile engineering and to the development of satellites where accurate knowledge of position, velocity, and orbit propagation are important mission parameters. Navigation activities are carried out in the Power Projection Systems Department (PPSD), SSD, and the Space Department (Table 1).

The SSD navigation activity has supported the Navy's Submarine Launched Ballistic Missile (SLBM) Program for over 40 years and helped to develop three generations of increasingly capable submarines and missiles. In addition, SSD contributes to the evaluation and improvement of tactical submarine (SSN) navigation systems. Submarine navigation-related tasks are conducted by SSD staff in four groups: Guidance and Navigation Systems, Systems Development and Operational Support, Prelaunch Systems, and Ocean Engineering. Tasks encompass modeling inertial navigation systems and their control systems; identifying trends in navigation systems performance; assessing the accuracy of periodic GPS or geodetic updates; planning and conducting special tests; developing instrumentation, ocean sensors, and imaging systems; analyzing real-time instrumentation data from submarine patrols and missile flight tests; and developing error-estimation software. These tasks produce estimates of system accuracy, reliability, operability, and environmental effects for use in deployment and target planning. To the submarine fleet operators, they provide specific recommendations to improve system capability through changes in operations, algorithms, hardware, or procedures.

The SATRACK/GPS Systems Group in SSD continues to upgrade SATRACK for improved SLBM weapon systems accuracy evaluation and reentry body analysis. This group is actively finding new applications for SATRACK technology. Improvements in the GPS constellation, coupled with missile antenna refinement and APL-developed post-processing upgrades, have led to significant gains in accuracy evaluation. SATRACK has uniquely supported range safety and accuracy processing of hundreds of strategic missile tests. SATRACK's unique tracking capability has found another application in BMD testing in which signals from both the interceptor and target missile are processed with the capability to develop relative intercept miss distances.

Navigation is crucial to all tactical weapon systems today for accurate determination of target location. Members of the Guidance, Navigation, and Targeting Systems Group of PPSD and the Systems Development and Operational Support Group of SSD have been developing means to accomplish this task. Sophisticated algorithms have been devised to determine accurate locations of targets in tactical imagery, such as might be obtained from an unmanned aerial vehicle using the sensor vehicle's navigation equipment, sensor models, and/or controlled national imagery—whatever support data are available. Accurate target coordinates can now be determined in minutes. Current efforts to increase automation will reduce that time even more.

A significant endeavor at the Laboratory is devoted to evaluating and predicting end-to-end navigation system performance using subsystem laboratory and field

**Table 1. Navigation activities.**

Department/group	Nature of work
Power Projection Systems Department Guidance, Navigation, and Targeting Systems Group Radio Frequency Missile Systems Group	Navigation systems analysis, modeling, and simulation GPS/Inertial Navigation System (INS) hardware systems testing Cruise missile mission planning Development and assessment of terrain- based navigation fixes High-precision mapping GPS-only and GPS/INS testing
Strategic Systems Department SATRACK/GPS Systems Group Guidance and Navigation Systems Group Systems Development and Operational Support Group Prelaunch Systems Group Ocean Engineering Group	Development of high-fidelity missile post-test reference trajectories Submarine navigation system accuracy and reliability assessment Error estimation algorithms Development of specialized GPS receivers, Kalman filters Special-purpose submarine, unmanned underwater vehicle/unmanned aerial vehicle, and road vehicle navigators Oceanographic measurements Development of special instrumentation, sensors, and imaging systems
Space Department Space Systems Application Group	GPS missile translators, data acquisition/ processing Spaceborne rad-hard GPS receivers and Kalman filter navigators Relative navigation of distributed spacecraft

tests, high-fidelity models, and flight-test analyses. The Guidance, Navigation, and Targeting Systems Group brings a broad end-to-end systems perspective, technology continuity, and a staff experienced in navigation modeling/simulation. NAVSIL, part of the Radio Frequency Missile Systems Group in PPSD, is also an important asset, carrying out the work of the department to evaluate new GPS/INS hardware and software, to validate analytical models used in simulations, and to develop and prototype new navigation concepts.

GPS is a very easy-to-use method to update a navigation system's location and velocity, but it is vulnerable to ECM. The DSMAC is an accurate means to update a navigation system, but it is difficult in mission planning to find scenes that will provide high-confidence all-day and all-weather updates. A current effort to satisfy all objectives (insensitive to countermeasures, available in all weather and at all times, easy to use) is called Precision Terrain Aided Navigation (PTAN). One key to the successful application of PTAN is the technology to rapidly generate high-resolution digital elevation maps (DEM). The staff within the Guidance, Navigation, and Targeting Systems Group is evaluating a variety of DEM generating technologies and assessing the impact of rapid processing technologies on the accuracy of

Tomahawk. If PTAN is successful for low-flying cruise missiles, its extension to platforms at higher altitudes will be examined. Other efforts within the group include developing technology to collect, process, and use high-resolution three-dimensional data (i.e., maps) over large areas. Staff in the Image Simulation Laboratory have developed software to render large maps (millions of elevation points) in real time. APL is now marketing this software.

Distributed spacecraft systems (also referred to as formation flying), enable complex sensing tasks such as wide aperture processing and co-observation to distinguish among spatial and temporal effects that impact observed data (Fig. 2). Both NASA and DoD have identified distributed spacecraft systems as a means to achieve future mission goals. The Space Department's

Space Systems Application Group has responded by establishing the Distributed Spacecraft Systems Program, which is developing the technology to support future distributed spacecraft missions.

A key technology development has been the Crosslink Transceiver, an integrated system that supports navigation, communication, and control among distributed spacecraft. The design of the Crosslink Transceiver leverages the Laboratory-developed GNS technology (see Navigation, Historic Highlights section). Additional elements include software developed for relative and absolute precision navigation, system hardware miniaturization for low power and mass, and a high-fidelity simulation of distributed spacecraft that supports mission operations studies. The successful development of these technologies for formation flying has positioned the Laboratory's Space Department at the forefront of this important new approach to enhance space science and terrestrial reconnaissance.

## GUIDANCE AND CONTROL

### Historic Highlights

For unmanned vehicles (i.e., missiles, spacecraft) the G&C system controls the vehicle velocity vector and



**Figure 2.** Distributed spacecraft systems are poised to revolutionize our vantage point from space. Space Department advances in spaceborne navigation, cross communication, and high-fidelity mission modeling are leading the development of this important new technology.

attitude. In general, G&C systems consist of onboard sensors (measuring attitude, vehicle motions, or homing distance), the guidance system (i.e., guidance filter, guidance law, and autopilot), and means of developing forces on the vehicle to affect a change in the motion. The onboard sensors can range from accelerometers and rate gyroscopes in an inertial measuring unit, to attitude measuring devices, celestial fixes, and homing signals from an infrared (IR) seeker or radar. The guidance system elements serve three different functions. The guidance filter takes noisy inputs from the sensors, filters the inputs through low-pass filters, and constructs a best estimate of the true vehicle motions and/or attitude. The guidance law receives the guidance filter outputs and determines what necessary kinematic corrections must be made to achieve the flight objective. These corrective action signals (commands) are passed on to the missile control system (autopilot). The autopilot determines the actions of the physical devices (i.e., tail fin deflections, thruster or torquer activation) that control the vehicle dynamics by creating forces.

Near the end of World War II, the Japanese resorted to kamikaze suicide attacks on the Fleet and the Navy decided that it needed to develop a surface-to-air guided missile for defense. As noted in the introduction, they formed Project Bumblebee to undertake the needed aerodynamic, propulsion, G&C, and airframe research and asked the Laboratory to lead various government and industrial agencies in developing the guided missile

technology. The primary effort of Project Bumblebee was the long-range, supersonic ramjet-powered Talos missile; APL played an important role in developing its radar beamriding guidance system.

In the early 1950s, increased maneuverability was needed to counter new threats and APL had a significant role in evolving tactical missile guidance from beamrider to semi-active homing. This success led to the deployment of the Terrier missile, which was designated Standard Missile when it was transitioned to modular construction in the 1960s. In response to the change in threats, there have been many generations and upgrades to Standard Missile; as Technical Direction Agent, the Guidance, Navigation, and Control Group of the Air Defense Systems Department (ADSD) has been at the forefront of G&C technology advancements.

In the 1970s, APL recognized the importance of flight simulation to analyze and predict tactical missile performance and led the way in developing high-fidelity six-degree-of-freedom (6-DOF) simulations for autopilot and guidance systems. Since that time, APL has led the development of 6-DOF simulations for Standard Missile with high-fidelity representations of autopilot and guidance systems, sensor systems, aerodynamics, propulsion and mass properties, seeker, and target.

To support APL work in tactical missile analysis and development, the Fleet Systems Department (forerunner to ADSD) established three dedicated facilities. The Guidance System Evaluation Laboratory (GSEL) provides for HIL simulation and testing and end-to-end testing of ship defense and BMD engagements. The Advanced Missile Simulation Laboratory (AMSEL), unlike GSEL, is strictly a high-fidelity all-digital computer simulation facility for the interceptor and weapon system. AMSEL employs large banks of high-end workstations and terabytes of memory to enable high-fidelity Monte Carlo simulation capability for system evaluation. The Actuator Test Facility, as its name implies, is used to evaluate steering control and thrust vector control hardware under simulated flight conditions.

In the mid-1990s, the Navy began developing two new Tactical Ballistic Missile Defense (TBMD) interceptors for the new defense mission against foreign threat missiles. The interceptor for Theater Defense is the SM-3 missile. The final stage of this four-stage missile is a controllable kinetic warhead with an IR terminal guidance system for exo-atmospheric intercepts (Fig. 3). The Area Defense missile is SM-2 Block IVA, which is used for both Anti-Air Warfare (AAW) and TBMD missions. As such, it has both radio-frequency semi-active and IR terminal guidance systems. As with previous variants, the Laboratory continues to provide the Navy with valuable technical expertise in concept development and system evaluation, and recommends design improvements for both of these systems to improve system performance for new and challenging missions.



**Figure 3.** The SM-3 kinetic energy (KE) warhead. As the SM-3 Round-level Technical Direction Agent, the Laboratory is supporting the development of the KE with independent engineering analysis of the Solid-propellant Divert and Attitude Control System (SDACS) and membership on the SDACS Integrated Product Team. APL is also providing independent evaluation of KE intercept flight performance using the NAVSIL and GSEL facilities.

G&C is also a critical discipline that has been successfully used in the Space Department for over 40 years of spacecraft development. As previously mentioned in the Navigation section, the Navy’s need for accurate navigation for its SLBMs led the Laboratory to be at the forefront in satellite navigation. The Space Department was formed to evolve the basic Doppler shift concept of navigation into a constellation of satellites under the Transit System. With the need for long-lifetime satellite stability, APL pioneered the gravity-gradient system for passive control.

Increasingly complex instrumentation and mission requirements set by DoD, NASA, and NOAA in the 1970s through 1980s led the Space Department to develop spacecraft with closed-loop momentum wheels coupled with Sun or magnetometer sensors for improved pointing accuracy. The MSX (Midcourse Space Experiment) spacecraft, developed in the mid-1990s, used a wide array of onboard processors and sophisticated attitude techniques to provide rapid slewing and precise arcsecond pointing accuracy. In addition to precise control, robust G&C designs helped to reduce the need for around-the-clock mission control. With improved G&C, near-autonomous operations were demonstrated with MSX, with resulting lower mission operations cost. The Laboratory has compiled a notable list of “firsts” in spacecraft G&C design.<sup>4</sup>

**Current Work and Important New Efforts**

APL’s G&C expertise provides a critical contribution to the Navy’s development of tactical missiles

and to the development of spacecraft and mission operations. G&C system design, analysis, evaluation, and development are carried out in ADSD’s Guidance, Navigation, and Control Group and the Space Department’s Mission Concepts and Analysis Group (Table 2).

The Guidance, Navigation, and Control Group is a center of expertise for the research, development, and testing of guidance, navigation, and control systems for ship defense and BMD missiles. The group supports concept trade studies and develops new G&C improvement algorithms, analysis methods, and design techniques through the application of advanced estimation and control theory. In addition,

the group provides technical direction to major Navy missile development programs through detailed assessment of proposed designs, investigation of design options to meet performance requirements, flight test predictions, and post-flight analyses. Design evaluations are performed with Monte Carlo analysis techniques using both the AMSEL high-fidelity 6-DOF digital simulation and GSEL HIL facility.

Current efforts include G&C support for the Navy’s SM-2 Block IVA and the SM-3. For the SM-3 program, G&C tasks are focused not only on the missile but also on the kinetic warhead (Fig. 3), which uses a solid propellant gas generator system and fluidic valves to control the attitude and divert the vehicle into the flight path of the threat missile.

The Space Department’s history of successful spacecraft development and mission operations can, in large part, be attributed to the work of the Mission Concepts and Analysis Group in developing robust

**Table 2. G&C activities.**

Department/group	Nature of work
Air Defense Systems Department Guidance, Navigation, and Control Group	Missile G&C design, modeling, analysis, and simulation Advanced G&C algorithm development Actuator testing
Space Department Mission Concepts and Analysis Group	Mission development support Modeling and simulation of systems and hardware Attitude estimation algorithm Graphical G&C systems design and automatic code development Spacecraft performance evaluation

G&C systems. The group performs G&C modeling and simulation to support mission planning; develops the onboard flight control software; specifies the requirements for the G&C onboard computer, sensor, and actuators and oversees their integration with the spacecraft; provides mission support; and performs spacecraft operational evaluation. Both the MSX and Near Earth Asteroid Rendezvous (NEAR) spacecraft epitomize the high level of robustness and capability provided by the modern spacecraft G&C design.<sup>5</sup> The Mission Concepts and Analysis Group makes extensive use of graphical control systems design tools to simulate and verify the G&C design and then automatically develop onboard code, thus avoiding the introduction of costly flight software errors.

APL staff are developing several advanced G&C technologies meant to improve the performance of future tactical missile interceptors. The need to engage ballistic missile threats and high-performance anti-ship cruise missiles is dictating the design of enhanced-performance missile interceptors that can provide high probabilities of kill. Classical missile G&C techniques now in use may not be able to achieve the needed interceptor performance (reduced time constants and increased lateral maneuverability) and robustness (gain/phase margins and robustness to uncertainty) to achieve needed kill probabilities.

To address this issue, ADSD's Guidance, Navigation, and Control Group is exploring two approaches to enhanced performance. The first is the Integrated Guidance and Control design, which combines the guidance filter, guidance law, and flight control logic into a single algorithm for optimized performance. This new G&C technique uses implicit knowledge of the airframe-plus-autopilot in a highly computationally intensive environment. Terminal homing 6-DOF simulation of this Integrated Guidance and Control technology shows reduced miss distance against weaving supersonic AAW threats and maneuvering endo-atmospheric TBM threats. The second approach being investigated is Multivariable Flight Control funded under an Advanced Technology Demonstration program. Monte Carlo 6-DOF simulations have shown that this hybrid of classic and modern control system design can enhance probability of kill; the next steps are HIL tests and a flight demonstration.

## AERODYNAMICS AND HYDRODYNAMICS

### Historic Highlights

Almost since its inception in 1942, APL has been a leader in the field of supersonic aerodynamics as it spearheaded the development of the ramjet-powered Talos missile for ship self-defense. This new area of

defensive weapon development required the Laboratory to pull together aeronautical engineers and physicists to conduct extensive wind tunnel tests and theoretical performance estimations. Characterizing the Talos airframe aerodynamics (i.e., aerodynamic forces and moments, stability and maneuverability, drag and engine inlet flow) was critical to the successful design.

With the need to engage high-altitude, high-g emerging threats, the Laboratory undertook extensive wind tunnel testing in the 1950s to characterize tail-controlled rocket-powered missiles. This work led to the development of the Terrier I missile. The Terrier I used large airplane-type wings for lift, but the wings caused shipboard handling problems. Aerodynamicists at the Laboratory conceived of the idea of switching from a winged design to four smaller but equally effective lifting surfaces called dorsals. This idea was an important milestone in the development of Terrier II missiles, and this basic design feature is found on every Navy Standard Missile and other tactical missiles fielded throughout the world.

The aerodynamic forces and moments (airloads) acting on a dorsal missile vary significantly with flight conditions. A thorough definition of the airloads was needed to develop the G&C autopilot, and in the 1950s Laboratory engineers in the Bumblebee Fluid Dynamics Group devised a robust protocol for wind tunnel testing and a modeling methodology that used the wind tunnel data to accurately represent the forces and moments acting on the airframe in all six degrees of freedom. The same protocol is still in use today.

In the late 1950s, the Navy began the high-priority national program of developing the Polaris FBM to be launched from submerged SSBNs. The technical issues associated with vertical launch from a slowly moving submerged submarine operating in the seaway were enormous, and engineers in the Laboratory's Polaris and Aeronautics Divisions made many important contributions in characterizing the hydrodynamics of underwater launch and in developing the launcher and missile systems.

In the mid-1970s, the Navy was concerned with enemy detection of its SSBNs; the Laboratory responded with the SSBN Security Program. This led to the formation of the Submarine Technology Department (now the National Security Technology Department) and a series of groundbreaking hydrodynamic activities. Those activities spanned decades and involved countless highly complex at-sea tests and laboratory tow-tank tests to characterize the submarine wake and to define the ocean's ambient background.

Also in the 1970s, as the need for higher speeds evolved for tactical missiles, the Aeronautics Department (now reorganized into the Research and Technology Development Center) focused on supersonic and hypersonic aerothermal heating of missile radomes. At

Mach 3 or higher flight speeds, radomes can be heated to temperatures of several thousand degrees and survivability and boresight error are of critical importance. APL directed the efforts of Corning Glass Works in the development of robust ceramic radome materials and then carried out critical radome aerothermal heating experiments at supersonic wind tunnels and a national solar heating facility.

Extreme aerothermal heating also occurs when vehicles and spacecraft undergo Earth reentry. The Aeronautics Department's experience in this area was requested by the Atomic Energy Commission (forerunner to the DoE) to conduct an independent assessment on the survivability of radioisotope power supplies used on interplanetary spacecraft in the event of accidental Earth reentry. The Aerospace Nuclear Safety Program was established in the early 1970s and the program continues today to provide independent engineering safety evaluations that factor into each Presidential Launch Approval decision.

In the mid-1990s, tactical missile aerodynamic work grew to support the development of the Navy's SM-2 Block IVA and SM-3 BMD systems. The principal aerodynamic activities encompassed development of high-fidelity aero models for the two interceptor airframes, experimental and computational fluid dynamics (CFD) analysis to ensure the survivability of the SM-2 Block IVA IR sapphire seeker window, and modeling of the aerothermal IR signature of threat and target test missiles.

**Current Work and Important New Efforts**

The Laboratory's aerodynamic and hydrodynamic capabilities reside in five departments and eight groups (Table 3). The work is focused on tactical missile aerodynamics, applied CFD aerothermal analysis, submarine hydrodynamics, underwater launch, and spacecraft noncontinuum flow.

For the Navy's BMD programs, the Laboratory continues to refine and evaluate from flight tests the high-fidelity, fully coupled 6-DOF aerodynamic models developed for the SM-2 Block IVA and SM-3 interceptors. As Technical Direction Agent for these interceptor development programs, the staff working aerodynamic and heat transfer

issues are evaluating and refining the engineering models of the SM-3 Kinetic Warhead Divert and Attitude Control System and supporting all facets of the development of the Block IVA IR seeker window system.

The SM-2 Block IVA interceptor is a challenging design from the perspective of its IR seeker. The seeker, side-mounted on the missile's forebody, is protected from the high-speed airflow by a hemispheric sapphire dome cooled with a jet of gas. There are complex interactions between the supersonic airflow and coolant flow that vary over the flight operational envelope. The gas coolant injected upstream of the dome significantly affects the temperature gradient on the dome and, consequently, dome survivability as well as the distortion through the window (boresight error), which affects target homing. In support of dome development, personnel in ADSD's Mechanical and Aeronautical Engineering Group have completed a comprehensive series of wind tunnel tests at the APL William H. Avery Advanced Technology Development Laboratory (AATDL) Aerothermal Infrared Test Facility Cell-4 as well as at numerous national wind tunnel and rocket sled facilities. An extensive series of CFD computations has also been completed. The task is in the final stages of providing a robust assessment of dome survivability, validating the onboard dome coolant flow algorithm, and providing a high-fidelity boresight error model Block IVA 6-DOF simulation.

**Table 3. Aerodynamics/hydrodynamics activities.**

Department/group	Nature of work
Air Defense Systems Department	Missile wind tunnel testing
Mechanical and Aeronautical Engineering Group	Missile aerodynamic modeling Aerothermal testing and computation Applied computational fluid dynamics Submarine hydrodynamics and missile launch
Research and Technology Development Center	Airbreathing engine inlets Aerothermal wind tunnel testing
Aeronautical Science and Technology Group	Experimental and computational fluid research
Physics Modeling and Application Group	
Strategic Systems Department	Underwater launch analysis and modeling
Missile Systems Evaluation Group	At-sea and tow basin testing
National Security Technology Department	Analytical and computational fluid dynamics submarine wake modeling
Engineering and Analysis Group	Theoretical and analytical models of oceanic, atmospheric, and environmental background
Oceanic, Atmospheric, and Environmental Sciences Group	
Space Department	High-altitude plumes/optical signatures
Mission Concepts and Analysis Group	Spacecraft/satellite outgassing, contamination

The SM-2 Block IVA and Theater-Wide (SM-3) BMD interceptors use an IR seeker for target homing. Accuracy models of the IR signature of a threat missile are needed for developing and testing the seeker. In support of that need, the Mechanical and Aeronautical Engineering Group has undertaken to improve and integrate the engineering software used to compute supersonic aerodynamic heating, the heating of the threat missile airframe throughout its flight, and the resulting IR image. This highly integrated engineering software suite has dramatically reduced the time to derive the IR signatures and provides physical parametric variation for Monte Carlo analyses. This new capability in IR scene generation is being used to simulate interceptor performance, to plan actual intercept tests, and to assess flight test results.

The Laboratory has a long-standing relationship with the Office of Naval Intelligence (ONI), performing “reverse engineering” on foreign threat missiles. An element of that work is scale-model wind tunnel tests of the airframe to predict flight performance. ONI funding is often low, which results in test compromises. Staff of the Mechanical and Aeronautical Engineering Group recognized this issue and proposed the idea of using fused deposition rapid prototype thermoplastic surfaces secured to a steel core backbone to reduce scale-model fabrication costs while maintaining the high structural rigidity needed to reduce distortion to airloads. Under Independent Research and Development funding, the hybrid rapid prototype models concept has been demonstrated in subsonic flow with results comparable to data obtained from traditional steel models at about one-third the cost<sup>6</sup> (Fig. 4). Work is ongoing to extend this new technology to address the need for quick-response wind-tunnel missile tests as well as to fabricate models of nonconventional airframes (e.g., stealth-designed unmanned combat vehicles) that are difficult to fabricate out of metal. The Laboratory is seeking patent protection for this new scale-model fabrication technology.

The Navy has initiated a significant new program to convert four Trident submarines into tactical strike platforms capable of launching up to 150 Tomahawk cruise missiles and transporting and delivering SEAL special operations forces for amphibious missions. The program is called Trident SSGN, and engineers in SSD’s Missile Systems Evaluation Group and ADSD’s Mechanical and Aeronautical Engineering Group are currently involved in studies to evaluate launch- and flowfield-related issues and support critical SSBN at-sea experiments.

The Engineering and Analysis Group in the National Security Technology Department (formerly the Submarine Technology Department) continues to improve models of submarine wake and nonacoustic detection signature. Both fully viscous CFD codes and empirical models are used to generate the submarine



**Figure 4.** Scale-model missile airframe fabricated using the hybrid rapid prototype process tested up to transonic speeds in a wind tunnel.

near-field wakes, which are coupled to an APL-developed wake evolution code for signature modeling. The signature models are being used to assess the stealth implications of newly proposed submarine designs. Staff in the Engineering and Analysis Group and the Oceanic, Atmospheric, and Environmental Sciences Group continue to plan and execute at-sea tests, gathering data on submarine flow and the ambient sea. The Research and Technology Development Center’s (RTDC’s) Fluid Dynamics Research Laboratory is an important asset used to make scale-model measurements of submarine-generated internal waves in stratified environment.

Some comment is offered on the discipline of CFD, as its use has grown significantly at the Laboratory in helping to solve fluid–structure interaction problems. Across APL, CFD is practiced by staff in four groups (Mechanical and Aeronautical Engineering; Aeronautical Science and Technology; Oceanic, Atmospheric, and Environmental Sciences; and Mission Concepts and Analysis) using commercial grid generation and flow solver codes. Computations are executed on either resident multiprocessor workstations (16- or 32-processor Silicon Graphics Origin Workstations) or at government-supported computational centers.

The CFD computations can focus on external (i.e., full airframe aerodynamics) or internal (i.e., ramjet engine flow) vehicle flow, incompressible (i.e., submarine hydrodynamics) and compressible (i.e., missile radome bow shock) flow regimes, and flows involving chemical reaction (i.e., rocket motor combustion). For missile engineering, CFD supports all aspects of the missile development process—conceptual design, detail engineering, and flight-test forensic evaluation.<sup>7</sup> Non-continuum CFD methods are used by personnel in the Mission Concepts and Analysis Group to model spacecraft outgas plumes and early portions of Earth hypersonic reentry. The importance of validating CFD results with data is heavily stressed at the Laboratory, and often

CFD and experimental tests are run concurrently and reinforce each other. APL's senior-level staff members that practice the art of CFD have a good understanding of the merits and current limitations of CFD and the importance of a balance between computation and experimental results.

## PROPULSION

### Historic Highlights

As noted earlier, the Laboratory's involvement in missile propulsion began when, as Technical Direction Agent for the Bumblebee Project, we took on the role of leading the development of a ramjet-powered supersonic missile. Just 6 months after the start of the project, Cobra, the first rocket-boosted, ramjet-powered supersonic missile, was successfully flown. Building on the success of Cobra, APL engineers proceeded to develop the ramjet engine for the Mach 2.7 Talos missile. The first-production Talos missiles came off the assembly line in 1955, although the ships needed to launch the missile would not be ready for another 3 years. Since decommissioning in the 1980s, Talos missiles have been converted to Vandal supersonic targets used for Standard Missile flight tests.

Since the success of Talos, research in ramjet propulsion for higher-speed missiles has continued to this day. In 1961, the ramjet-powered Typhon missile successfully flew seven times at Mach 4 during the flight test program. While Typhon never entered service because the missile could outfly the fire control system at the time, it established the state of the art in supersonic airbreathing missiles. Typhon research continued on a wide variety of ramjet and ducted rocket-powered missile concepts; however, none made it to flight. A summary of some of the key APL ramjet development programs can be found in Refs. 8 and 9.

In the early 1960s, the Aeronautics Department was formed to develop more efficient ramjets, improve the aerodynamics of airframes, and support missile launchers. Part of the focus of the propulsion effort shifted to even higher speeds than could be attained by conventional ramjet engines. The Laboratory led the way in the development and application of supersonic combustion ramjet (scramjet) engines for missile applications to enable speeds in excess of Mach 5. This work resulted in the development of the Supersonic Combustion Ramjet Missile (SCRAM), which successfully demonstrated net positive thrust at Mach 7 in wind tunnel tests.

To better support the advanced research necessary for ramjet and scramjet engines, APL built the Propulsion Research Laboratory, which was at the time a state-of-the-art wind tunnel complex for scramjet, capable of simulating flight conditions up to Mach 7 for testing integrated missile concepts. The facility (now known as the AATDL) occupies 5 acres on APL property

and consists of five blowdown wind tunnels (or cells) capable of simulating a wide range of Mach number, altitude, and elevated temperature conditions for direct connect and freejet engine tests.

In the late 1970s, features in ramjets and scramjets were brought together in the Dual Combustion Ramjet (DCR) concept. The DCR was a unique APL invention that coupled a subsonic combustion chamber with a supersonic combustion chamber to enable the use of conventional liquid hydrocarbon fuels for hypersonic flight. Previous supersonic combustion ramjet engines required the use of toxic and highly reactive fuels not suitable for shipboard use. The DCR concept was demonstrated through a series of component test programs through the mid-1980s, at which time the Laboratory effort in hypersonics shifted to the National AeroSpace Plane (NASP) Program.

APL made major contributions to the development of NASP engine technology, including performing long-duration, large-scale scramjet combustor testing from Mach 5.7 to 13.1, the first time such testing had ever been conducted at such a high speed. APL also ran the large-scale high-speed inlet test that provided important data on inlet operation up to Mach 16.5.<sup>10</sup> NASP ended in 1994 and the Laboratory returned focus to the DCR for missile applications; it is this technology that forms the backbone of current APL efforts in airbreathing propulsion.

Along with airbreathing propulsion systems, the Laboratory has had a long-standing role with solid-fuel rocket propulsion engineering. In the mid-1940s, APL became headquarters for the Chemical Propulsion Information Agency (CPIA), which is the nation's repository for all rocket motor data. CPIA transferred to the JHU School of Engineering in the 1990s and continues to be a vital source of data on all aspects of rocketry. Currently, Laboratory staff skilled in rocket propulsion specialize in the analysis and design of rockets for Navy tactical missiles. The Space Department also maintains capabilities to assess and select commercially available chemical and cold gas thrusters for satellite reactive control. The flawless rendezvous and gentle touchdown on Eros by the NEAR spacecraft in 2000 is a vivid example of successful thruster spacecraft integration.

### Current Work and Important New Efforts

Propulsion and propulsion-related work is carried out in five groups, with the preponderance of research and development activities performed in RTDC's Aeronautical Science and Technology Group (Table 4). The primary propulsion technology development strength is in hypersonic airbreathing propulsion engines—from component design to integrated engine tests, through airframe integration. The AATDL staff and facilities are highly respected throughout the airbreathing propulsion community.

**Table 4. Propulsion activities.**

Department/group	Nature of work
Research and Technology Development Center	Hypersonic airbreathing engine technology development
Aeronautical Science and Technology Group	Rocket propulsion technology advisement Hybrid rocket/airbreathing propulsion analysis High-temperature materials testing Propulsion system analysis, modeling, and design
Air Defense Systems Department Mechanical and Aeronautical Engineering Group	Rocket motor performance modeling Kinetic Warhead Divert and Attitude Control System oversight
Strategic Systems Department Missile Systems Evaluation Group	Propellant systems aging and reliability
Space Department Space Mechanical Systems Group	Satellite and spacecraft propulsion technology application
Technical Services Department Mechanical Services Group	Propellant aging analysis

Current efforts in airbreathing propulsion at APL are focused on the continued development of a DCR-based hypersonic missile concept; however, the concept is now being applied to time-critical strike mission needs instead of air defense. Under the joint Defense Advanced Research Projects Agency/Office of Naval Research-sponsored Hypersonic Flight (HyFly) Program, the Laboratory is serving as lead Technical Advisor to mature a hypersonic strike missile through a series of increasingly complex flight experiments (Fig. 5). APL has developed and successfully demonstrated a full-scale missile combustor at Mach 6 test conditions and is preparing to test a full-scale DCR flowpath from tip to tail in wind tunnels at Mach 3.5, 4, and 6. The goal is to demonstrate sustained Mach 6 cruise out to several hundred nautical miles by 2005. The Laboratory is once again leading the way into a new frontier for missile flight just as in the days of Talos.

NASA continues to pursue technologies for more efficient Earth-to-orbit propulsion systems for future access to space vehicles. One propulsion concept being investigated by Aeronautical Science and Technology Group staff is the rocket-based combined-cycle (RBCC) engine, which promises to offer the desirable features of both rockets and airbreathers in a common design. Engineers are developing analytical engine models, performing system-level studies, and developing a technology roadmap for further NASA RBCC development.

Exo-atmospheric BMD interceptors employ hit-to-kill kinetic energy vehicles to destroy the threat missile.

Jet thrusters are used for divert and attitude control; however, current systems under development for the Navy use solid propellants with complicated thrust modulation schemes. The Aeronautical Science and Technology Group is currently working on a hybrid system that uses a solid fuel with liquid oxidizer. The prototype hybrid system is being tested at simulated altitude in the AADTL. Critical issues to be addressed are package energy density, thrust-level predictability, and thrust switching times.

For chemical rockets, staff of the Aeronautical Science and Technology Group and Mechanical and Aeronautical Engineering Group that are experienced in solid propellant ballistics and boosters continue to play an important role in Integrated Product Teams for future variants of the Navy's Standard Missile interceptor

and kinetic energy kill vehicle thruster systems. The Space Department's successful NEAR mission and the recent contract award from NASA for the New Horizons mission to Pluto and the Kuiper Belt highlight the Laboratory's continued reaches into interplanetary space. Our experience with commercially available conventional thrusters has been proven with the NEAR and MSX spacecraft; however, deep space exploration may require the use of exotic propulsion systems such as ionic propulsions, and the Laboratory may need to develop more experience in these areas.

The successes of the NEAR mission are being exploited with enhanced propulsion and control designs for complex trajectory and control systems. For example, MESSENGER will require a challenging



**Figure 5.** Under the Office of Naval Research's Hypersonic Weapons Technology Program, the Research and Technology Development Center is serving as lead Technical Advisor in the development of an affordable airbreathing hypersonic missile to address long-range, time-critical targets.

thruster-powered turn to achieve Mercury orbit insertion. The STEREO mission deploys dual spacecraft, each in a large elliptical phasing orbit. These must be carefully controlled to target precise flybys of the Moon for gravity-assisted trajectory maneuvers to send each spacecraft on independent trajectories—one ahead of the Earth, the other trailing the Earth. STEREO has the added challenge of minimizing disturbances to long experiment booms when firing thrusters during Moon targeting maneuvers. Excessive attitude motion would degrade targeting and could endanger the spacecraft.

## CONCLUSIONS

The work of the Laboratory in the disciplines of navigation, G&C, aerodynamics/hydrodynamics, and propulsion has played an important role in the development of military platforms, missiles, and spacecraft for over 50 years. Our sponsors in DoD, NASA, and other government agencies have a keen understanding of the value we bring to solving their weapon system and space mission goals. Across the Laboratory, vehicle technology work is accomplished in five departments with a staff of about 165. The depth of knowledge of our exceptionally capable staff in the four vehicle technology fields is a key factor that enables the Laboratory to participate in a wide range of activities—from the high-level weapon system concept trade studies, to designing spacecraft missions, developing vehicle system performance models and simulations, designing detailed hardware, and planning and carrying out critical tests. We provide unbiased technical performance evaluations, serve as Technical Direction Agent, and actively participate in Integrated Product Teams when appropriate.

Across the four vehicle technology disciplines, there is a long list of APL-invented or -conceived breakthroughs. To support our work we have developed important resources, including RTDC's AATDL, PPSD's NAVSIL, and ADSD's AMSEL, Actuator Test

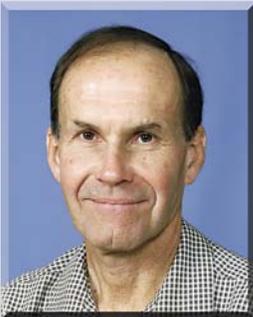
Facility, and a CFD-dedicated computational resource. While no one can accurately predict the next evolution of weapon system and spacecraft needs, the Laboratory's staff, facilities, and analysis software in the four key vehicle technology disciplines will be capable of meeting these vehicle development challenges.

## REFERENCES

- <sup>1</sup>Guier, W., and Weiffenbach, C., "The Genesis of Satellite Navigation," *Johns Hopkins APL Tech. Dig.* **19**(1), 14–17 (1998).
- <sup>2</sup>Hatch, R. R., Luber, J. L., and Walker, J. H., "Fifty Years of Strike Warfare Research at the Applied Physics Laboratory," *Johns Hopkins APL Tech. Dig.* **13**(1), 113–124 (1992).
- <sup>3</sup>Thompson, T., Levy, L., and Westerfield, E., "The SATRACK System: Development and Applications," *Johns Hopkins APL Tech. Dig.* **19**(4), 436–447 (1998).
- <sup>4</sup>Jenkins, R., "Advanced Spacecraft Technology Program," *Johns Hopkins APL Tech. Dig.* **20**(4), 620–630 (1999).
- <sup>5</sup>Strikwerda, T., Ray, J., and Haley, D., "The NEAR Guidance and Control System," *Johns Hopkins APL Tech. Dig.* **19**(2), 205–212 (1998).
- <sup>6</sup>Heisler, R. R., and Ratliff, C. L., "Wind Tunnel Model Design and Test Using Rapid Prototype Materials and Processes," in *Proc. 10th Annual AIAA/BMDO Technology Conf.*, Paper No. 5-4 (Jun 2001).
- <sup>7</sup>Frostbutter, D., McGrath, B., and Rogér, R., "Application of Computational Fluid Dynamics in Missile Engineering," *Johns Hopkins APL Tech. Dig.* **22**(3), 289–301 (2001).
- <sup>8</sup>Keirse, J. L., "Airbreathing Propulsion for Defense of the Surface Fleet," *Johns Hopkins APL Tech. Dig.* **13**(1), 57–68 (1992).
- <sup>9</sup>Waltrup, P. J., White, M. E., Zarlingo, F., and Gravlin, E. S., "History of Ramjet and Scramjet Propulsion Development for U.S. Navy Missiles," *Johns Hopkins APL Tech. Dig.* **18**(2), 234–243 (1997).
- <sup>10</sup>White, M. E., "The National AeroSpace Plane Program and the APL Role," *Johns Hopkins APL Tech. Dig.* **13**(1), 218–232 (1992).
- <sup>11</sup>*The First Forty Years: A Pictorial Account of The Johns Hopkins University Applied Physics Laboratory Since Its Founding in 1942*, ISBN: 0-912025-00-X, Schneiderets and Sons (1983).

ACKNOWLEDGMENTS: This article covers a very broad area of work across many departments and groups; it could not have been written without the help of many people. The author would like to recognize and thank leaders at the Laboratory in the four disciplines and Senior Leadership Team poster presenters for their help in providing information for this article. Particular thanks are offered to Fred Riedel, Neil Palumbo, Michael E. White, and Tom Strikwerda for their guidance, insight, and help in writing this article. A special thanks is offered to the many contributors to Ref. 11, as it provided a rich and valuable history base. In addition, thanks are offered to John Commander for his editorial prowess in helping to assemble this article and for his previous help in preparing the Vehicle Technology plenary session presentation.

## THE AUTHOR



JOHN J. WOZNAK holds a B.S. from Lowell Technological Institute and an M.S. from the University of New Hampshire, both in mechanical engineering. He attained the rank of Captain in the Air Force in 1968 and worked on fluidic fuzing systems at the Air Force Weapons Laboratory, Albuquerque, NM. In 1973 he joined the APL Strategic Systems Department and in 1979 transferred to the Fluid Dynamics Group of the former Aeronautics Department, where he specialized in hydrodynamics, fluid mechanics, and computer modeling of missile underwater launch, towed vehicles, and tactical missile aerodynamics. In 1995 Mr. Wozniak became Supervisor of the Fluid Dynamics Group and also initiated the Advanced Natural Gas Vehicle project. He is now Supervisor of the Mechanical and Aeronautical Engineering Group in ADSD, which supports a wide variety of weapons system and spacecraft development activities encompassing design, thermal and structural analysis, CFD dynamics, and wind tunnel testing. He is a member of APL's Principal Professional Staff and holds seven patents, including several for medical devices developed in collaboration with the Johns Hopkins Hospital. His e-mail address is john.wozniak@jhuapl.edu.