



Science and Technology Supporting Vehicle Development at APL

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The Laboratory's Air and Missile Defense, Precision Engagement, Space, and Undersea Warfare business areas continue to pursue technology advancements in guidance, navigation, and control (GNC), aerodynamics/hydrodynamics, propulsion, and support systems to meet emerging challenges facing missiles, undersea platforms, and spacecraft. These challenges are diverse and far ranging and are being addressed through investment in highly trained personnel, specialized laboratories, and independent research. Efforts highlighted here include GNC algorithm research, navigation improvement vis-à-vis data fusion, GNC system evaluation facility upgrades, improvements in high-resolution digital elevation mapping, technologies to improve submarine communications at depth, missile aerodynamic performance and IR signature prediction, spacecraft technology advancements, advancement in both acoustic and nonacoustic sensors for unmanned underwater vehicles, and buoyancy "powered" undersea gliders.

INTRODUCTION

For nearly 60 years, APL has played an important role in advancing the disciplines of guidance, navigation, and control (GNC), aerodynamics/hydrodynamics, propulsion, and support systems for missiles, spacecraft, and undersea platforms. In broad terms, this work is classified under the Laboratory's science and technology taxonomy of "vehicle technology," and many APL technical specialists have made important contributions to the development of such practical vehicles that support the Laboratory's prime business areas and critical missions important to our sponsors.

In this article we discuss the vehicle disciplines in the context of the Laboratory's business areas of Air and

Missile Defense (AMD), Precision Engagement, Space, and Undersea Warfare (USW), focusing on changing sponsor needs and the approach being taken by APL to meet emerging challenges. At the onset it needs to be recognized that the Laboratory is a problem-solving organization, and our main strength is systems engineering. This is especially true for complex vehicle systems for which we generally perform applied engineering of emerging technologies developed by the technical community at large. In general, APL is a "fast follower/early adopter" of emerging technologies and recognizes the value of the technology and the appropriateness of insertion to solve new problems.

Vehicle systems also involve structures, sensors, communications, and payloads that interact or impact the disciplines addressed in this article. Many of these other elements of vehicle technology are covered in separate articles within this issue of the *Technical Digest* (e.g., structures discussed by Biermann et al., and air-breathing propulsion addressed by Van Wie et al., this issue).

VEHICLE TECHNOLOGY

Air and Missile Defense

The AMD business area focuses on the application of science and technology to enhance naval weapon systems for all forms of AMD for the U.S. Navy and allied operations. This defense is against a threat that is global and in a dynamic state of flux. Both cruise and ballistic missile threats are proliferating throughout the world at an alarming rate. Emerging powers can acquire missile technologies or complete systems from other nations willing to sell their technology to support their economies. It is estimated that more than 25 countries have the capability to launch intermediate-range ballistic missiles. In addition to the changing threat, there is also a change in the operating environment. With the end of the Cold War, the threat to the Fleet is found within littoral waters, with engagement by low-flying cruise missiles launched below the ship's radar horizon.

Defeating the above threats poses critical technological challenges to defense missile systems. Intercepting ballistic missiles in the exo-atmosphere (above an altitude of 100 km) necessitates a technologically advanced kinetic warhead (KW) with a sophisticated IR seeker coupled with a precise divert and attitude control system. Destroying a ballistic missile threat with a hit-to-kill KW occurs with relative closing velocities measured in kilometers per second and with allowable miss distances in centimeters. Similar challenges abound for defeating supersonic sea-skimming threats that can pull avoidance maneuvers when recognizing that the general engineering "rule of thumb" is that the interceptor must be able to pull 3 times the acceleration of the threat.

One component in the Navy's arsenal to counter these threats is the family of Standard Missile (SM) surface-to-air missiles, designed with maximum flexibility and growth through the use of interchangeable parts and modules.¹ For the past 30 years, SM has provided an important layer of defense to our naval forces and continues to evolve in response to technically advanced threats and challenging operating environments. The SM mission includes anti-air warfare sea-based Theater Ballistic Missile Defense (TBMD), and advanced versions are in various phases of development to defend against the Overland Cruise Missile and supersonic sea-skimming threats. Numerous advancements in

seeker technology, GNC, propulsion, and aerodynamics are under development to offer the highest probabilities of kill against the evolving threats. In addition, there are important cost, international interoperability, and reliability issues that must be factored into all technological solutions. To that end, the AMD business area is working closely with the Navy to help define a strategy for evolving SMs to support these important 21st century blue water and littoral maritime operations.

Work in the AMD business area concentrates on algorithm research, flight hardware and software development, simulation and test,² seeker technology, and advancements in aerodynamics. Algorithm research is associated with guidance filters, guidance law, autopilot, attitude estimation, navigation computations, and filtering. Flight hardware projects deal with the onboard computers, control actuators, inertial sensors, and GPS receivers, while software tasks entail onboard code and its validation. GNC simulation and test are major tasks associated with component test, high-fidelity six-degree-of-freedom (6-DOF) simulations, and system validation through hardware-in-the-loop functional testing.

Algorithm Research

A growing direction for APL is algorithm development because new algorithms provide the greatest potential for performance gain. The heart of an air defense missile GNC system is the set of algorithms for estimating target and missile states, the guidance law that develops missile acceleration commands, and the flight control system to achieve the commanded acceleration. The essential goals of algorithm design are to ensure robust performance against expanding threat envelopes and to mitigate the impact of parametric variations caused by manufacturing tolerances, aerodynamic variations, missile mass property variations, and changing environments. Developing and assessing algorithms is achieved through detailed models and simulations that capture the relationships between the closed-loop missile dynamics and the dynamics of ever-more-capable threats.

In the 1990s, APL conducted several studies to investigate the applicability of robust control methods to missile GNC. These early studies showed promise and resulted in an Advanced Technology Demonstration, sponsored by the Office of Naval Research, to improve the responsiveness of missile systems via multivariable robust control. Another key area of research was investigating performance improvements by tighter integration of the GNC functions based on differential game theory. The principal outcomes of these studies were an approximate factor of 2 improvement in the interceptors' time responses and a reduction in miss distance by up to a factor of 2 under stressing engagement conditions.

Those earlier algorithm activities have been broadened into a general framework of algorithm research. Missile improvement metrics have been established along the lines of operational flexibility, lethality, flyout reliability, and development time. Some of the ongoing and planned algorithm topics for investigation include tightly/loosely integrated GNC, nonlinear integrated GNC, information-sensitive guidance, automated tuning, and integrated guidance and navigation.

Another area of algorithm research focuses on enhancing KW probability of hit. Because of KW maneuver limits, performance improvements may be gained by an intelligent coupling between target discrimination and guidance when widely spaced threat objects are involved. Information-sensitive guidance is directed at the notion that the guidance law should incorporate the state estimate uncertainties of the selected guidepoint, as well as that the generation of the guidepoint itself should account for discrimination uncertainties. This concept also applies to the BMD boost phase intercept problem, where significant uncertainties exist in the future trajectory of the threat.

Flight Software and Hardware

Complementing GNC algorithm research are tasks associated with the implementation of advanced algorithms within the missile-borne, real-time processor. One research area of high payoff is directed at rapid prototype transition from 6-DOF algorithm development code to real-time flight code through a Matlab Simulink-based approach or a more customized direct coding approach using C. This technique uses graphical design tools extensively to simulate and verify the GNC design and then develop onboard code. In addition to accelerating onboard code development, this approach also helps avoid the introduction of flight software errors.

Software-embedded control and simulation is another area offering future flight software payoff. This technology uses common processor hardware architecture for analytic simulation, real-time simulation, and flight hardware. One concept being explored is the use of a common middleware to facilitate the interconnection of disparate platforms and software. Recent work has shown the potential advantages of this common middleware, but further work is needed to ensure that real-time software performance is not compromised.

A persistent constraint in the development of advanced GNC algorithms is the limitations of current real-time missile-borne processors. Advanced GNC algorithms can quickly grow to "fill up" any current processor design that might be a viable tactical system. Although significant real-time missile-borne processor advancements will undoubtedly continue, missile-borne computer processing power historically lags behind that of engineering computers used in the laboratory.

Thus, as GNC algorithms advance, a major challenge is their implementation within a missile-borne real-time processor.

Missile flight hardware advancements are also being pursued to improve missile agility and robustness. Areas of investigation include all-digital actuators and combining thrust vector control (TVC) with aerodynamic control. All-digital fin actuator systems offer the advantages of lower power consumption and finer control and performance robustness compared to analog systems.

The concept of using rocket motor TVC combined with aerodynamic control (i.e., tail fins) has been used with air-to-air missiles and is now being considered for ship self-defense. Offering increased agility immediately at launch is important for close-in engagement of supersonic sea-skimming threats. Aerodynamic fin control cannot produce a significant pitching moment early in flight, when the missile velocity and dynamic pressure are low. The AMD business area is actively investigating the feasibility of developing an adjunct TVC system that can be discarded after redirecting the interceptor. APL engineers have gathered system requirements (packaging, maneuverability, weight limit, electrical power, and cost goal) and performed a trade-off study for jet vane, jet tab, and domed deflector alternatives. The trade-off analysis led to the down-select of the most promising concept. The Navy has given the go-ahead to develop a prototype and perform a piggyback test during a rocket motor static ground firing with the eventual goal of a future flight demonstration.

System Evaluation and Test

As part of the AMD strategic plan to provide critical engineering to our Navy and Missile Defense Agency (MDA) sponsors, APL is investing significant resources into GNC system evaluation and test facilities. The enhanced Guidance System Evaluation Laboratory (GSEL)³ facility upgrade includes the addition of a cryogenic space chamber (\$2M) and a system for the mechanical motion of multiple targets (\$1.5M), as well as advanced RF and IR target generators (\$1.5M) to support development of both SM-3 (TBMD) and SM-6 (extended-range anti-air warfare) variants.

Investments in APL's Navigation Systems Integration Laboratory included increasing the size of the original facility, enhancements to support new navigation architectures, and a major upgrade of the dynamic wavefront simulator to assess advanced GPS anti-jam systems.

The Actuator Test Facility (ATF) is another investment area. The ATF is used to test and evaluate missile and KW control and actuation systems as well as related technologies. Divert and attitude control systems (DACS) provide KW stabilization, maneuverability, and attitude control. DACS use a system of highly responsive valves to dither the flow of gas to thrusters, creating complex dynamics that are difficult to

measure using standard pressure sensors and/or strain gauges. Recognizing the growing importance of missile defense work, the new testing facility is being designed to support highly dynamic DACS thrust testing using cold gas.

Seeker Technology

The AMD business area maintains a strong presence in missile seekers with traditional technologies employing semi-active or active RF and passive IR. APL is also actively exploring emerging technologies such as laser radar (ladar). Detailed knowledge of seeker technology is critical in assessing missile performance for target acquisition and tracking, interceptor homing, threat discrimination, and end-game engagement.

A major element of our TBMD work is characterizing the performance of the KW's strap-down IR seeker. APL does this by developing models of the seeker hardware and software, including detailed models of the radiance signature (e.g., the effect of threat motions) and high-fidelity models of the seeker hardware (e.g., the telescope optics blur, focal plane array spatial filtering and noise, and digital simulation of the seeker's real-time flight software). Seeker assessments are performed with 6-DOF digital simulation in APL's Advanced Missile Simulation and Evaluation Laboratory driving a hardware-in-the-loop model in the GSEL.

One of the most critical and most challenging seeker problems for TBMD is the accurate and timely discernment of the object carrying the lethal payload. The payload must be identified in the presence of other objects within the ballistic threat complex, such as spent boosters and attitude control sections, and may also include unintentional deployment debris and intentional countermeasures, such as decoys, jammers, and chaff. The discrimination process begins before launch of an interceptor missile, extends beyond the point of intercept, and depends on the threat type, operational engagement geometry, RF and IR sensor characteristics, command and control (C2) architecture, networking (data fusion) strategies, and interceptor-missile guidance.

In response to this critical challenge, the AMD business area has established the Ballistic Missile Defense Discrimination Independent Research and Development (IR&D) task to develop the expertise, models, and collaborative framework to address the discrimination problem from a system-level perspective. The task was initiated in 2001 and has changed from year to year to reflect progress made and to address new concerns. Four focus areas with associated tasks have been identified, covering phenomenology, sensor technology, and information processing.

1. *RF discrimination features and RF physics-based scattering* addresses performance trade-offs of advanced RF discrimination features.

2. *Ladar in BMD* focuses on developing models of the ladar signatures of ballistic missiles and rocket plumes and evaluating algorithms for identifying the target.
3. *IR discrimination* examines novel approaches to assist single-color IR discrimination.
4. *Information processing/sensor fusion* investigates the applicability of Bayesian networks for fusing sensor data.

Total IR&D investment for target discrimination is \$2M through FY2005, with the potential for significant payoff to both the Laboratory and our MDA sponsors.

Aerodynamics

Air defense missile performance is enhanced at APL via improvements in airframe aerodynamics being tackled through wind-tunnel testing and computational fluid dynamics (CFD). Some of the areas in which the Laboratory is making important engineering contributions are in developing high-fidelity, fully coupled aerodynamic models or "aeromodels" (forces and moments) of advanced airframes; predicting threat missile hardbody and rocket motor plume IR signatures; and improving the agility of future interceptors. Other vehicle aerodynamic-related work, such as the aerothermal analysis of advanced missile radome materials, can be found in other articles of this *Technical Digest* issue.

APL has a long history of developing aeromodels for tactical missiles and has evolved a very robust aeromodel architecture that captures, in high fidelity, the six components of force and moment acting on the airframe from launch to target intercept. High-fidelity aeromodels are an important element of 6-DOF flight simulations and are critical in autopilot algorithm development. Traditionally, aeromodels are derived from an exhaustive series of wind-tunnel tests to encompass the full set of flight conditions from launch to endgame engagement. Hundreds of additional post-test hours are then expended to analyze the data, render the data into an aeromodel, and validate the aeromodel against the original wind-tunnel data.

Complementing wind-tunnel testing is CFD, which has taken on an ever-increasing role supporting missile engineering. Properly applied, CFD has proven to be a capable adjunct to testing if benchmarked with data. In recent years the term "virtual wind-tunnel" has evolved, referring to the idea of developing aerodynamic "data" with a high-end workstation.

A multi-year plan has recently been initiated to combine the virtues of CFD with time-honored wind-tunnel testing and "knowledge-based" assistance to accelerate the development of aeromodels. The goal is a 50% reduction in the time and cost of developing an aeromodel without a meaningful loss in fidelity.

In a related area, APL continues to develop rapid prototype (RP) fabrication technology to build low-cost

wind-tunnel missile-scale models. APL's patented hybrid/RP technology uses a metal core for structural rigidity, with all outer surfaces formed from a variety of RP part "build-up" processes (stereolithography, fused deposition, and selective laser sintering) directly from computer-aided design files. RP industry improvements in material bulk properties, tolerance control, and surface finish are enabling scale models with higher fidelity and higher Mach number capability. The technique also allows complex airframe shapes (i.e., blended-body shapes, Fig. 1)⁴ to be fabricated with microsensors embedded. This pacesetting development has led to work with new sponsors and expanded applications.

In support of TBMD, APL has also developed a high-fidelity, physics-based simulation to predict the IR signatures of threat missiles. IRIS (IR imaging software) is a suite of interrelated codes that predicts the 3-D supersonic flow over an airframe; determines the transient aerothermal heating, accounting for internal structure, material charring, and ablation; and develops the radiance signature. Target missile radiance images, collected during numerous flight tests, have validated the fidelity of IRIS results. The IRIS suite has dramatically reduced the time to derive high-resolution resolved IR images and parallelized processing in a LINUX environment, while supporting Monte Carlo analyses for complete 6-DOF trajectories. This new capability in IR scene generation is being used to simulate interceptor performance, plan actual intercept tests, and assess flight test results. IRIS is continuously evolving, with models to simulate liquid/solid fuel rocket motor plumes, countermeasures, debris, and ablation wakes, and is an important element in APL's growing business with MDA.

Performance requirements for the rapid and robust responsiveness of future ballistic missile interceptors, both in and out of the sensible atmosphere, make a compelling case for the use of reaction jets for diverting the flight path and controlling attitude. A technical challenge with reaction jets within the sensible atmosphere is a phenomenon known as jet interaction (JI), which is associated with the interaction between the reaction-jet exhaust and the oncoming airflow over the missile. The JI phenomenon must be characterized fully for autopilot design and to achieve reliable flight performance.



Figure 1. Air Force unmanned combat air vehicle RP wind-tunnel model constructed by APL.

Within the aerospace community, JI research focuses on scaling cold-jet wind-tunnel data to hot-jet flight conditions, investigating JI afterburning and transient jet phenomena, and correlating CFD with testing. The Laboratory has performed some limited JI wind-tunnel tests and CFD analyses (Fig. 2), but more importantly has helped to formulate a multi-year technology roadmap for improving understanding of the underlying physics and translating that to meet aerodynamic performance objectives.⁵ Although the future of JI research funding is unclear, what is clear is that reaction jets offer the potential for dramatic responsiveness which will be needed to counter stressing threats.

CFD has grown significantly at APL over the past decade in support of vehicle technology and is practiced to back a variety of sponsors and business areas. Its science and technology importance cannot be underrated. CFD analyses focus on external compressible flow (supersonic airframe aerodynamics) and internal compressible flow (ramjet engine flow), incompressible flow (submarine hull flow and wake), flow involving chemical reaction (rocket motor combustion and plumes), and noncontinuum flow (spacecraft outgases and drag during the initial phase of reentry). In missile engineering, CFD supports all aspects of the missile development process⁶: conceptual design, detail engineering, and flight-test forensic evaluation.

In recognition of the importance of the discipline of CFD, there has been a significant investment in personnel, software, and multiprocessor computer workstations across the Laboratory. This investment is providing and will continue to support many sponsored tasks.

Precision Engagement

The Laboratory's Precision Engagement business area involves the application of offensive military power and

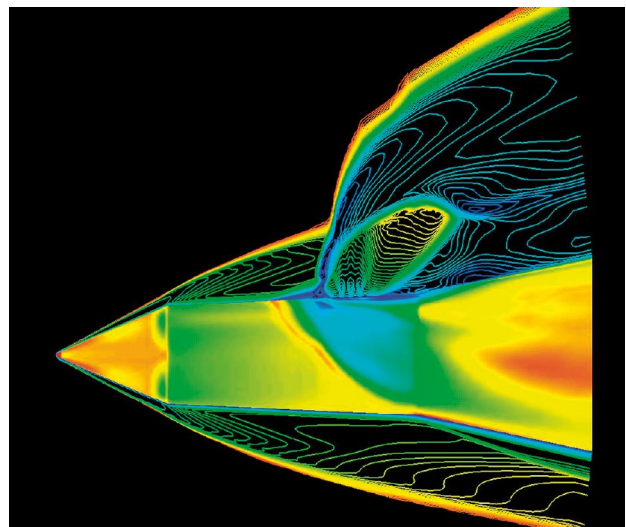


Figure 2. JI CFD analysis: a supersonic interceptor firing a center-of-gravity thruster.

includes launch platforms, weapons, and C2 systems as well as command, control, communications, computers, intelligence, surveillance, reconnaissance, and targeting systems (C4ISRT) and the warfighters that operate them.

APL has been the Technical Direction Agent for the Tomahawk Weapon System since the early 1980s, involved in nearly every aspect of its development and deployment. In navigation, APL has made scientific and engineering contributions to the Tomahawk Land Attack Missile (TLAM) terrain matching system Terrain COntour Matching (TERCOM), precision targeting with digital scene matching area correlation (DSMAC), and assessment of the susceptibility of its GPS navigation system to electronic countermeasures (ECM). Precision terrain aided navigation (PTAN) is an evolving navigation upgrade to overcome some of the shortcomings of DSMAC, and the Laboratory is supporting that effort through the development of technology to rapidly generate high-resolution digital elevation maps. Staff in the Image Simulation Laboratory have developed and are now marketing software to render large maps (millions of elevation points) in real time.

An upgraded version of the TLAM under development, called Tactical Tomahawk or TacTom, adds the capability to reprogram the missile while in flight to any GPS target coordinates. It also will be able to loiter over a target area for some hours, and with its onboard TV camera, allow the warfighting commanders to assess the battle damage of the target, and if necessary, redirect the missile to any other target.

The near-term future for precision engagement is directed toward successive navigation upgrades to improve system responsiveness, ECM immunity, accuracy, and operational flexibility. This includes working with deeply coupled GPS tracking algorithms, fusion of data from multiple sensors, further development of global net-centric surveillance and targeting, and development of less expensive guidance systems without sacrificing accuracy.

Civilian and National Security Space

Given current scientific and military priorities, spacecraft development is headed in two important directions: small, responsive, and distributed spacecraft and large space systems. This two-pronged approach to the development, demonstration, and acquisition of space systems, and the science and technology underlying their successful implementation, can provide a systematic means to achieve a broad set of U.S. goals. Two fundamental challenges exist in achieving success: (1) technology development and infusion and (2) effective programmatic and acquisition approaches. Much has been accomplished in meeting the technology development challenge. The more difficult challenge is effectively developing a cost-effective acquisition

strategy and executing the space program while managing the confluence of civilian, military, and commercial interests in an industry with financial uncertainties and an inadequate industrial base in some areas.

Small, Responsive, and Distributed Space Systems

Small spacecraft that can be deployed for short-term (e.g., 1 year) tactical military missions, or several spacecraft that can be launched from one launch vehicle, have generated significant interest within civilian and military agencies. Military planners see small, low-cost spacecraft as a means to rapidly deploy new or extended capabilities to directly support combatant commanders in the field. The envisioned missions include tactical sensor augmentation such as dedicated hyperspectral imagers, synthetic aperture radars, signal intelligence, and force tracking operations. This concept is represented by the Air Force's Operational Responsive Space/Joint Warfighter Space Systems.

Civilian missions for small, multiple spacecraft have the scientific benefit of distributed assets for measurements, experiments, and data collection. Missions of interest envision the use of such systems in three canonical ways: (1) multipoint sampling, (2) co-observation, and (3) interferometry. Multipoint sampling uses distributed spacecraft to simultaneously collect data, typically *in situ*, across a field of interest so that spatio-temporal effects are observable. An example is NASA's Magnetospheric Multiscale (MMS) instrument, which will measure 3-D structures of various sizes within the Earth's magnetosphere using four spacecraft flying in loose formation. A similar APL concept is embodied in the Auroral Multiscale mission (Fig. 3) that was conceived to sample the structures within the Earth's aurora. Co-observing missions rely on additional coordination among distributed space assets to cooperatively observe targets of interest. The NASA Leonardo mission concept envisions using at least six spacecraft to provide 3-D observations of bidirectional radiative forcing functions in regions throughout the Earth's atmosphere. Finally, interferometric missions envision extremely aggressive control of space systems to coherently observe regions or targets. Such systems typically have extensive requirements for navigation, communications, and control among distributed assets, and significant technology advances are necessary to achieve the vision of such interferometric systems.

To support distributed spacecraft mission goals, APL has pursued technology development in enabling areas such as navigation, communications, propulsion, payloads, and C2. The APL Crosslink Transceiver (CLT) is a miniature system that provides absolute and relative navigation as well as crosslink communications and basic command and data handling capabilities.⁷⁻⁹ The transceiver comprises a radiation-hardened processor,



Figure 3. APL's multiple-satellite Auroral Multiscale mission concept.

a miniature GPS receiver, and crosslink transmit and receive modules that allow communications and direct ranging and timing among multiple spacecraft. This technology provides essential navigation and communications functions in a miniature, low-power system with a design that readily extends capability through the addition of uplink/downlink modules. The CLT can also accept ultrastable oscillator inputs for precision interferometry missions.

In addition to navigation and communications, a challenge for many space systems is agility to execute many maneuvers to obtain optimal location for a measurement or operation. This challenge is more difficult in small spacecraft because of power limitations and propulsion systems that tend to require a large percentage of a spacecraft power budget. Through an ongoing IR&D effort, APL is developing a small-scale, low-power pulse plasma thruster system (Fig. 4) that could give future spacecraft significant propulsion capabilities under power-limited conditions.^{10,11} Results to date have demonstrated a highly competitive system that is easy to implement and integrate on a spacecraft and can work with a wide range of propellants for tuning its performance.

To help overcome the size, mass, and power constraints of small spacecraft buses that must deliver aggressive payloads, APL has focused on the development of both miniature, low-mass payloads and payloads that are adaptive and reconfigurable. This encompasses concepts for lightweight optics for multiband (e.g., visible and IR) and hyperspectral imagers. Under APL's

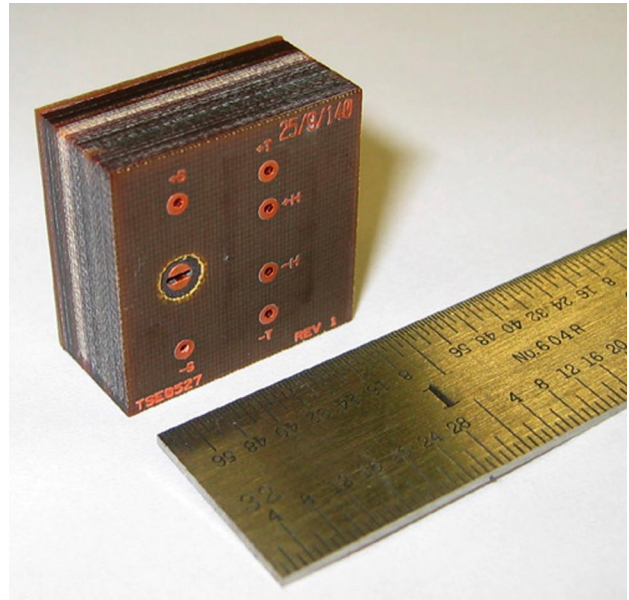


Figure 4. APL-developed pulse plasma thruster engineering model.

Military and Civilian Space IR&D program, an optics system has been designed that supports the compact packaging of a large-aperture system on small spacecraft buses. In terms of reconfigurability, APL has pursued the implementation of space-qualified software-programmable technology for communications systems, and indeed, the CLT can be dynamically configured to operate in several modes, including different forms of multiple access (e.g., time division or frequency division in conjunction with code division).

As a systems engineering laboratory, APL has focused on the development of techniques for the C2 of distributed, autonomous spacecraft. Initial emphasis was for onboard C2 techniques such as applying discrete event dynamic systems and model-based reasoning to provide a formal means to model and control extremely complex systems in a dynamically adaptive manner while maintaining the ability to test, verify, and validate system operations.¹² Through the National Security Space IR&D program, this research has been extended to include autonomous ground systems that allow tactical commanders to call up services from available spacecraft and provide direct tasking of payloads.

In addition to technology development and infusion efforts, APL is working with partners at the Naval Research Laboratory for the Office of the Secretary of Defense/Office of Force Transformation (OSD/OFT) to address critical acquisition challenges for the DoD in the context of developing small, tactical spacecraft. Specifically, through OSD/OFT's Operational Responsive Space Bus Standards program, APL is leading the systems engineering team that is working with industry to define and implement a set of standard spacecraft bus interfaces. This experiment will enable the

government to acquire larger quantities of low-cost spacecraft from multiple vendors and with consistent performance through adherence to those validated standards.

Large Space Systems and Deployable Structures

While a great deal of development is ongoing in small, tactical, and distributed systems, significant classes of problems are best solved through space systems that use large structures. Such missions include those that require significant power-aperture for high-resolution sensing and large bandwidth communications. Among other missions that are particularly applicable for large structures in space are systems for exploring the structure and evolution of the universe; an example is NASA's Terrestrial Planet Finder to study the existence, characteristics, and evolution of planets outside our solar system. System designs to address these challenges often require a commensurate increase in the fundamental aspects of a spacecraft bus such as a very large solar array area for power generation or an alternative power source.

Another significant research and discovery thrust that requires large structures is the NASA Exploration Initiative, which envisions lunar basing as a step toward further exploration of the solar system. Such a concept requires the ability to assemble structures in space, or on the lunar surface, and the ability to supply and maintain such bases. Furthermore, achieving the goals of the Exploration Initiative requires the ability to develop, implement, and maintain essential infrastructural capabilities that are ubiquitous in the terrestrial environment such as navigation and communications infrastructures throughout the Earth–Moon system.

APL science and technology efforts in support of large space-based structures have focused on particular niche areas that represent a high-risk, high-payoff approach. Examples are payload and antenna designs that exhibit very large deployed-to-stowed ratios. The National Security Space IR&D program in folded optics supports very high bandwidth communications antennas in volume-limited space applications in a scalable manner and expands the availability of optical receivers for space systems. Another area of research has developed and demonstrated a hybrid inflatable antenna (Fig. 5) for RF communications. The advantage of this design is that a core traditional dish antenna, providing moderate-bandwidth communications, is enhanced by an inflatable annulus that is deployed and rigidized after spacecraft kickoff from the launch vehicle. This inflatable annulus enables large-aperture high-bandwidth communications as an augmentation to the fixed-structure lower-rate antenna.

Although both military and civilian agencies are driven to large-scale space structures for various applications, a fundamental challenge remains the ability to

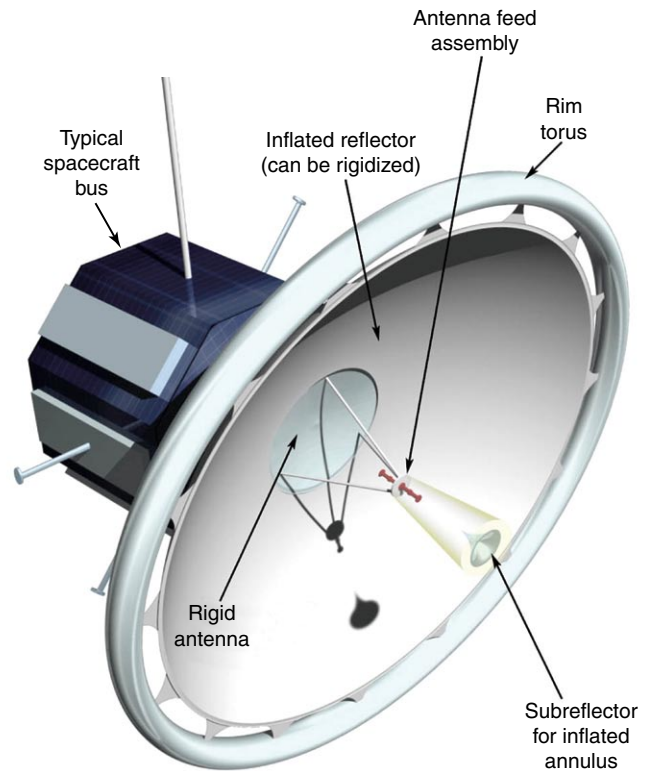


Figure 5. APL's hybrid inflatable antenna.

acquire such systems within acceptable cost constraints. NASA's civilian approach to this challenge has been to fund a small number of space science observatories on a priority basis. To assist the military in such decisions, and specifically for the Defense Advanced Research Projects Agency (DARPA), APL has helped to characterize the combined technical and cost challenges of acquiring large-scale and often distributed systems through development of a functional/cost modeling system. DARPA has used this tool to help assess the feasibility, from an acquisition perspective, of pursuing certain DoD space system applications and the enabling technologies needed to implement them.

Undersea Warfare

APL's USW business area has its origins with the SSBN Security Program and has grown to encompass anti-submarine warfare (ASW), the development and deployment of ocean engineering systems, and mine warfare analysis.

The major challenges to be addressed include development of an overarching USW system-of-systems framework to support the 2020 vision, continued investigation of advanced and autonomous acoustic and nonacoustic sensors, distributed systems, integration and management of diverse and multiple USW resources, force defense and security, and communications.

Unmanned Systems and Sensors

A transformational ASW concept is unmanned autonomous vehicles. The Laboratory has been engaged in requirements development, trade studies, and assessments of various unmanned undersea platforms since the late 1980s in support of various Navy organizations. In this process, APL has been involved in defining USW missions for unmanned underwater vehicles (UUVs), looking ahead to potential applications in 2015 and beyond. Trade studies have indicated that the current development concept and timelines will have to change dramatically. A limited number of UUV variants, with the ability to have quickly modified payloads packages, need to be developed to obtain a reasonable cost per mission (reasonable such that the loss of a vehicle is not cost-prohibitive or critical to the success of the mission). Reduced costs can be achieved by manufacturing a defined set of configurations, in large quantities, and standardizing interfaces with payload modules. Several potential UUV missions have been identified. Decomposition of the missions into UUV capabilities (such as search rates, data processing, endurance, etc.) lead to various UUV classes. Some issues that affect UUV size and missions include the interface/deployment platform and the resulting impact on size, weight, payload distribution, energy, power consumption, and even refueling-related issues. Critical technologies include communications (frequency, data rate, content), navigation accuracy, autonomy, and energy. UUV missions may include ISR, mine countermeasures, ASW, and oceanographic mapping.

The Laboratory has been developing significant capability in emergent control for unmanned systems such as a simulation tool for comprehensive testing of complex multivehicle engagements. With extensive high-fidelity ocean acoustic models, a quantitative value of the detection ranges achievable for acoustic apertures that could be supported on a UUV can be determined.

APL leads a team that proposes to demonstrate innovative survivable undersea gliders, advanced sensors (acoustic and nonacoustic), autonomous processing, and *in situ* environmental assessment for sensor placement optimization to provide a rapid-response, long-duration, relocatable, and survivable undersea surveillance capability. The concept is to create a large-area “meta-sensor” based on data generated by each node of the sensor grid. Each node is an undersea glider with an advanced sensor suite. The data collected at each node are processed in the node and then relayed back to a field fusion engine that fuses the sensor grid data with data from other sources (e.g., SIGINT). Gliders (Fig. 6), which operate by changing buoyancy and gliding

in a vertical saw-tooth profile, enable silent operation (no propeller), the ability to surface or equilibrate at a selected depth, the ability to station-keep as required, long-range and extended endurance, and the ability to fly themselves into an area or to reposition themselves. The proposed glider design has a capability to dive to the ocean bottom, thus optimizing the efficiency of the buoyant propulsion design. The relocatable nature of the gliders supports tactical repositioning of assets and allows the vehicle to return to base for refurbishment.

In addition, APL is examining the research and development requirements to advance the capabilities of underwater glider technology within the next few years, e.g., a hybrid version of the glider (a “motorglider”) optimizing between glider mode and battery-driven thruster mode. The Laboratory would determine the scaling rules for the dimensions, performance, and cost of underwater gliders and motorglider hybrids; determine the attributes and limitations of underwater gliders and motorgliders; and identify optimal operational regimes within the performance envelope of each functional category.

Another current APL developmental project, similar in operational concept to a glider/sensor node, has a low-power DSP-based processor board with data input from a glider-mounted planar hydrophone array. The DSP can run complex signal processing algorithms within the node itself. These algorithms include low-frequency analysis and ranging generation, line-of-bearing estimation, and data compression. Processing the data within the sensor reduces the number of false alarms as well as power consumption for longer system life. The prototype system has been built that incorporates a compass and GPS and can communicate over Iridium, GlobalStar, or Freewave radio.

Navigation

Four basic techniques are used when navigating underwater vehicles (whether submarines, remotely operated vehicles, or autonomous underwater vehicles): dead reckoning, inertial, acoustic baseline, and radio. Each technique navigates the vehicle in a relative coordinate frame that can be referenced to a geodetic

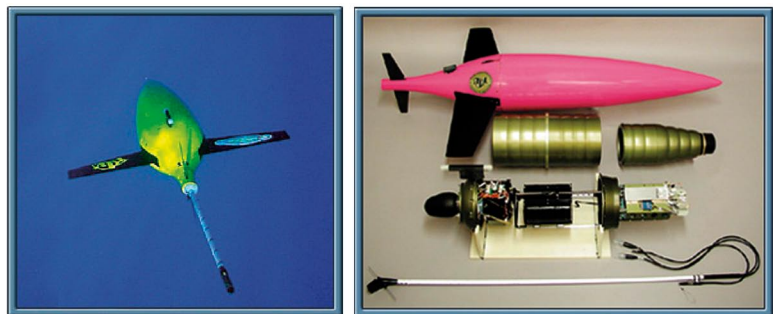


Figure 6. Buoyancy-propelled autonomous marine glider: (left) ocean test and (right) internal components.

location via off-board sensors with established geodetic locations or alternatively to the initial geodetic location and orientation of the onboard sensors and vehicle. Although each technique alone can successfully navigate a vehicle, a more accurate system may be achieved by combining or integrating the sensor outputs from two or more techniques via a Kalman filter.

Current efforts are being made to provide an infrastructure for the transmission of differential GPS corrections. These systems yield position accuracies on the order of 1–5 m. To get accuracies on the order of centimeters, additional navigation data at a higher update rate are needed. There is potential to take advantage of the existing infrastructure with supporting stations to provide wide-area coverage for precise positioning. The availability of wide-area precise positioning could benefit all vehicle types, including surface ships. The potential ability to support multiple applications using existing infrastructure makes precise vehicle positioning using GPS an important technology area to pursue.

The Laboratory's Ocean Systems Group has been leading the Navy's effort to develop technologies that enable GPS reception and global communications by submarines operating at patrol depths. These technology developments established GPS reception from a submarine-compatible buoyant cable antenna (BCA) in an at-sea test that demonstrated L1 GPS (1575 MHz) reception as well as accurate position determination using the GPS BCA and a flexible architecture GPS receiver (FAR). Both the BCA and the FAR were products of Laboratory IR&D funding. Following the project's proof-of-concept success, the Navy funded a demonstration of the system onboard an SSN. The GPS BCA maintained legacy VLF/HF reception capabilities while adding accurate GPS position determination as the ship operated far below periscope depth.

The GPS BCA system concept used a small-diameter (0.65-in.) antenna to limit detection while floating on the ocean surface; however, the small diameter created an antenna that "clothes lines" across wave crests in higher sea states. This posed difficulties in RF reception and antenna GPS position fix determination. The solution was an antenna assembly designed with three elements, each independently able to close the GPS downlink; as long as these elements were separated to prevent simultaneous washover, GPS reception could be supported using the FAR.

During the SSN at-sea demonstration the three GPS BCA antenna elements allowed clear reception of the satellite signals greater than 80% of the time with the submarine operating at a variety of depths, well below periscope depth, and at speeds up to 3 kt. The FAR was designed to operate with snippets of GPS signals from each of the BCA elements, enabling it to accumulate downlink signals and produce position fixes whenever the BCAs were on the sea surface.

The GPS BCA concept of multiple antenna elements operated independently or as high-gain steerable beams has been extended to two-way communications using the L-band Iridium link and to small, flexible UHF antenna elements. The BCA communications antenna concept maintains the small antenna diameter to preserve stealth and limit the cost to deploy the system.

For the GPS BCA, the location of the submarine is uncertain relative to the antenna, which floats several hundred feet above and behind the submerged submarine. The submarine's position must be estimated using catenary models that operate without knowledge of interceding ocean environmental conditions that affect cable shape. APL has explored the feasibility of using acoustic signals to aid in determining the position of the ship relative to the BCA. The method involves a time-tagged in-water acoustic signal emanating from the GPS BCA assembly and subsequently received onboard the submarine. The acoustic waveform is actually generated onboard the submarine and then used to feed an acoustic source at the antenna assembly.

SUMMARY

For the past 60 years, the Laboratory has played an important role in the development of missiles, spacecraft, and undersea vehicles for our DoD and NASA sponsors through the applied engineering disciplines of GNC, aerodynamics/hydrodynamics, and propulsion. Building on that success, APL is continuing its investment in highly trained personnel, specialized laboratories, and independent research to position us to support our existing sponsors and make important contributions to our nation's defense and scientific discovery.

Key to supporting the AMD business area is the investment in GNC algorithm research, flight hardware/software development, systems test and evaluation facilities, IR&D seeker technology advancement, and developments in aerodynamics and CFD to enhanced missile and KW performance. Challenges in the Precision Engagement business area are being served through work on navigation systems that are less susceptible to GPS and ECM jamming through the fusion of multiple sensor data, the development of tools to support rapid weapon system targeting, and technologies to dramatically impact weapon system operational flexibility. The Civilian and National Security Space business areas have made significant investment in enabling technologies for miniaturized and low-power navigation and communications systems, plasma thrusters, dynamically configurable payloads, and C2 technologies to reduce ground cost and enhance overall system effectiveness. Future APL-developed spacecraft will offer expanded access and capability with improved performance based largely on technology advancement investments. The USW business area is focusing on the transformational challenges

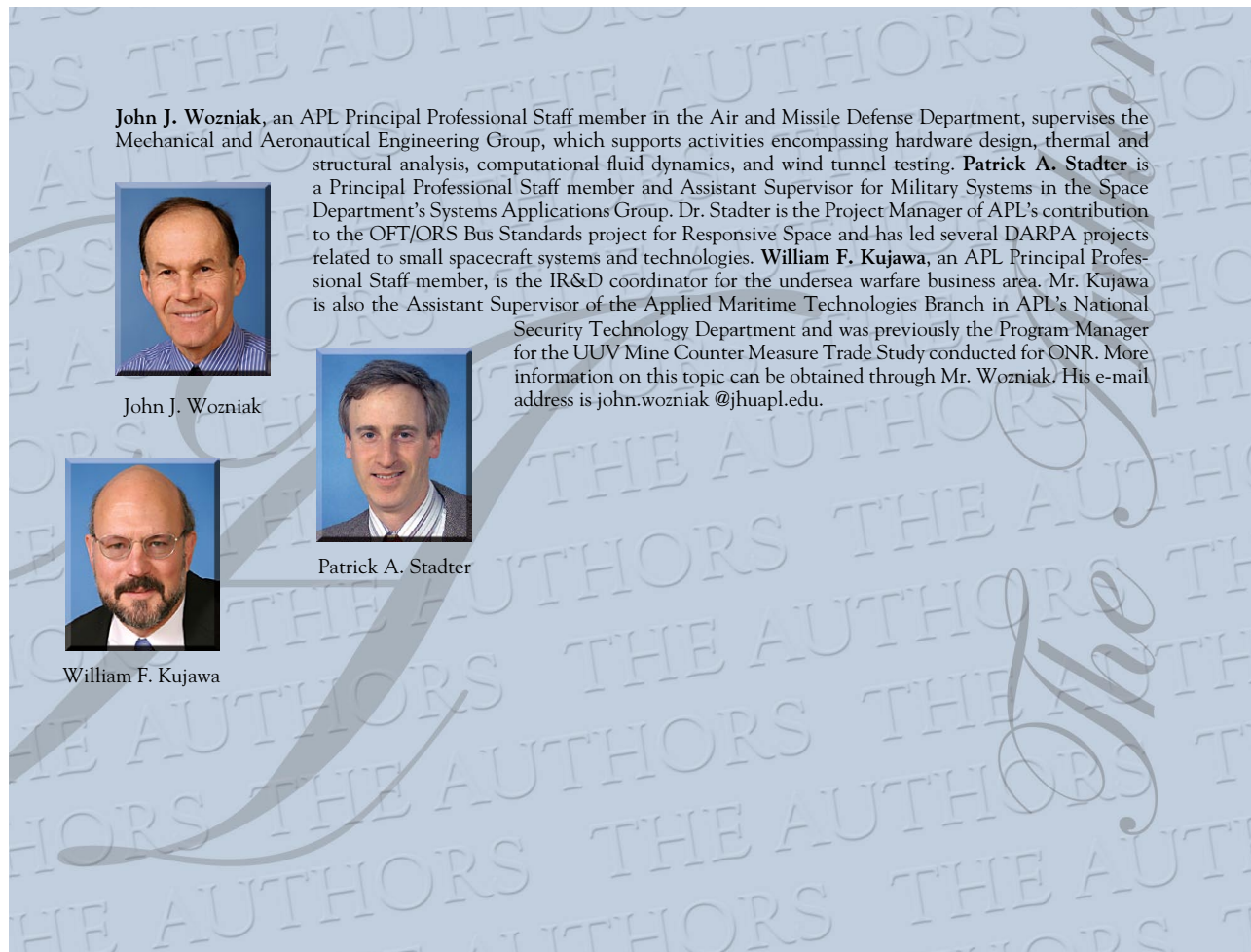
associated with submarines and autonomous UUVs, including the development of reliable submarine GPS navigation and global communications vis-à-vis buoyant cable antennas, and advancing the application of autonomous UUVs to support critical ASW, mine clearing, and oceanographic mapping undersea missions.

While no one can accurately predict the next evolution of weapon system and spacecraft needs, the Laboratory's staff, facilities, and independent research investments in the four key vehicle technology disciplines will help us meet future challenges.


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