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POWER PROJECTION

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Front Cover: *Power Projection,* Illustration by Alvin Quiambao

SPEAKING OF S&T

▶▶ By Rear Adm. Mathias W. Winter, USN

This first edition of *Future Force* for 2015 is appropriately focused on power projection. U.S. naval capability must be relevant and decisive where it matters, when it matters. This means Navy and Marine Corps commanders need the technological advantages necessary to project power and influence. They require technologies that enable a full range of options across the continuum of naval operations. This will ensure our naval warfighters can help keep the peace and fight the fight when called upon.

Department of the Navy research and development investments in the past have enabled us to strengthen and enhance our forces today. This work is critically important, and the dedicated community of naval scientists and engineers in the Naval Research Enterprise are the unsung heroes who discover, develop, and deliver new technologies every day for our Sailors and Marines.

For example, in 2014 the Navy successfully deployed and operated a new prototype laser cannon aboard a ship in the Arabian Gulf. Laser weapons are powerful, cost effective, and provide instantaneous speed-of-light engagement. In addition, the electromagnetic railgun is a revolutionary advancement in naval gun technology. It delivers unprecedented safety for a shipboard weapon system and can fulfill multiple mission requirements for Sailors and Marines. Recent advancements in the railgun will enable initial shipboard testing in 2016.

Both lasers and railguns are high-powered precision electric weapons with game-changing capabilities that will revolutionize how we employ warships, meet modern security challenges, and deliver power projection at a fraction of the cost of traditional missile systems.

In this issue, several articles go into more detail about high-energy laser systems, the railgun, and the ongoing research into power systems necessary for this new class of weapons, such as breakthroughs in materials, power and energy (generation, storage, and delivery), and electronics. Other science and technology (S&T) milestones in this issue include innovations in over-the-horizon amphibious capability for the Marine Corps, expanding tactical communication with nanosatellites, and autonomous swarming technology that enables unmanned systems to work collaboratively together. Autonomous systems can help reduce risk to our warfighters, extend capabilities, and lower operating costs.

Advanced technology is the result of many people working together. Partners are critical to sharing innovation and cost in the S&T process, and in "Future Watch" we feature a partnership between the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency to develop long-range air vehicle technology for small-deck ships. The program, called Tern, will be completed in 2018 and aims to improve intelligence, surveillance, and reconnaissance capabilities for destroyers and littoral combat ships, which often operate independent of land- or carrier-based aircraft.

As the new chief of naval research, it is my honor and privilege to have the opportunity to lead an incredible team of highly talented and innovative people. Since 1946, ONR has guided the investment of S&T research for the Navy and Marine Corps, enabling many important technical breakthroughs at the Naval Research Laboratory, naval warfare centers, and across industry and academia. In the near future ONR will publish the updated Naval S&T Strategy, which will provide more insight and details on how the Naval Research Enterprise will pursue our S&T needs, challenges, and opportunities.

Together, we will continue to solve some of the most complex technical challenges facing our naval forces and nation. I look forward to the breakthroughs ahead!

Rear Adm. Winter is the chief of naval research.

Power Projection:

Power Projection encompasses the weapon systems that allow naval forces to direct hard combat power to the horizon and beyond and under the sea, on land, and in the air, as well as the enabling and supporting technologies that make that power possible.

Photo by MC1 Eric Dietrich.

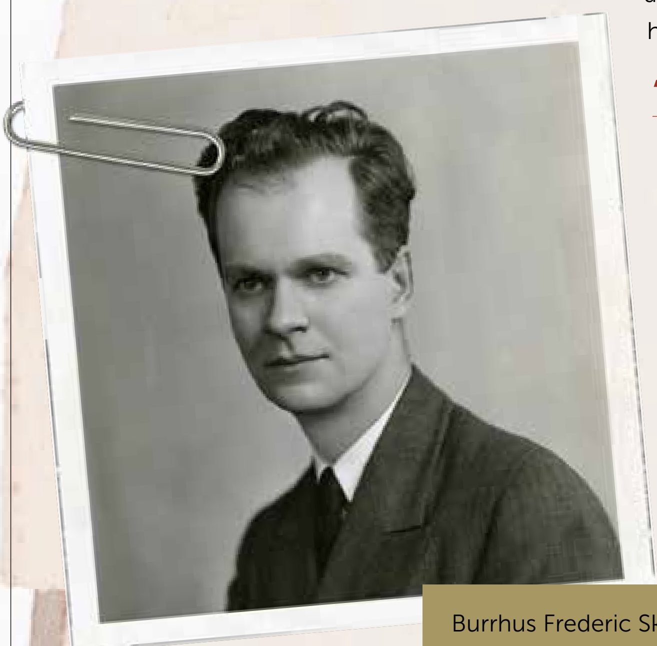
HOW WE GOT HERE

By Colin E. Babb

In a war that had seen perhaps history's fastest expansion of ideas for how humans could kill more of their own species, as well as cause increasing amounts of collateral damage, one weapon technology demonstration in the spring of 1944 may not have been the craziest of ideas. But it was close.

In the midst of World War II, a psychologist had a crazy idea that pigeons could guide bombs. Even crazier was the fact that it almost worked.

Psychologist B.F. Skinner and a small team of researchers were making their final appeal to the National Defense Research Committee (NDRC) for an ordnance guidance system that used pigeons as the guiding "mechanism." While there were some problems with the program—integrating the nose cone, which contained the pigeons, with the missile—the pigeons themselves did their job perfectly. "But the spectacle of a living pigeon carrying out its assignment, no matter how beautifully," Skinner wrote years later, "simply reminded the committee of how utterly fantastic our proposal was. I will not say that the meeting was marked by unrestrained merriment, for the merriment was restrained. But it was there, and it was obvious our case had been lost."



Burrhus Frederic Skinner received his Ph.D. in psychology from Harvard in 1931 and was a professor at the University of Minnesota when World War II began. Photo courtesy of University of Minnesota Archives, University of Minnesota-Twin Cities.

"A Crackpot Idea"

The concept, on the surface, was quite simple: One or more carefully trained pigeons inside the nose cone of a bomb or missile would peck on a screen-projected image of a ship or other target. As the target grew closer, the image would get bigger, and the pecking on the screen would be transmitted electrically or mechanically to control mechanisms in the weapon, guiding it—hopefully—to the target. Needless to say, the pigeon (or pigeons) was not expected to survive the encounter.

In 1940, Skinner initially envisioned his animal-based guidance system as a way to shoot down aircraft from the ground—an early surface-to-air missile concept before practical versions of such weapons even existed. As the war progressed, his guidance system was planned for air-to-ground (or surface) missiles. Skinner and his colleagues were responding to very real technological problems:

Illustration by Alvin Quiambao

B.F. Skinner’s final nose cone prototype was fitted for three pigeons. The three worked together, jointly providing “data” that would make the weapon—it was believed—more accurate. The prototype is now at the National Museum of American History in Washington D.C. Photo courtesy National Museum of American History, americanhistory.si.edu.

how to mitigate the high casualty rates of combat flyers, and how to increase the accuracy of air-dropped ordnance. Not only was it dangerous being a flyer in World War II—some 160,000 American and British Commonwealth airmen became casualties in the strategic air campaign over Europe alone—those who did make it through to targets usually had to hit them in large numbers because of the low accuracy of contemporary bomb-aiming equipment.

Radio control, a promising guidance method, was actually several decades old by the beginning of World War II. Basic experiments with British and American remote-controlled aircraft proved the concept in World War I, and the U.S. Navy used the old battleships *North Dakota* (BB 29) and *Utah* (BB 31/AG 16) as radio-controlled target ships in the interwar years. The Germans were the first, however, to use guided air-to-surface munitions in combat. On 9 September 1943, aircraft from *Kampfgeschwader* 100, carrying the Fritz X radio-controlled glide bomb, heavily damaged the Italian battleship *Italia* and sank its sister ship *Roma*—the day after Italy surrendered to the Allies and switched sides. Over the next week, the same Luftwaffe unit damaged numerous Allied ships off the coast of Italy during the invasion at Salerno, using either the Fritz X or the rocket-powered Henschel Hs 293. Both the Americans and British, however, quickly discovered that the radio signal guiding these bombs could be jammed electronically. A mini-arms race ensued as both sides sought to create new control and jamming units through to the end of the war.

Radar also was a good candidate for early guided munitions. The Pelican—a U.S. glide bomb developed for the Navy by the NDRC in 1942—originally was tested with a semi-active radar homing system that involved releasing the weapon from a PV-1 Ventura aircraft, which would have an active radar emitter that would send a signal picked up by a passive radar receiver aboard the Pelican. Early radars, however, were of short range and often suffered from interference from other emissions. For those designing the Allies’ guided weapons with these experiences in mind, there was room for guidance systems that used something other than the electromagnetic spectrum.

Employing "Operant Conditioning"

It was in this context that Skinner proceeded with his work in 1943 and 1944. Skinner was an expert in the field of behavioral psychology—he would go on to be a pioneer in the field and one of the most well-known psychologists of the 20th century. His work during the war revolved around the concept of "operant conditioning." This type of conditioning was meant to prompt specific behaviors without the use of certain stimuli—as with Ivan Pavlov's salivating dogs in which bells are able to produce a similar response to food. Salivation was a behavior the dogs already were capable of; operant conditioning sought to train animals to perform new behaviors. Skinner's early work, profiled in a 1937 *Life* article, involved training a rat to take a marble and drop it down a hole to receive a bit of food. At the beginning of the war, Skinner thought he could apply this kind of conditioning to pigeons to get them to control bombs or missiles.

The lowly (or hapless) pigeon—long a companion of Soldiers on the battlefield as a (sometimes) cooperative messenger—was not an unfamiliar animal to Sailors in the Navy. USS *Langley* (CV 1), the first U.S. aircraft carrier, originally carried pigeons meant to be used to deliver messages from aircraft back to the carrier. (The pigeons proved to be even less cooperative for this task, however, than their Army brethren.)

Skinner, in his laboratory at the University of Minnesota, concentrated on designing a special nose cone to be fitted on the Pelican glide bomb. Early experiments had the pigeons mounted in a little harness that controlled the bomb's movement as the pigeon's head moved up and down or left and right. The concept seemed to work well enough that Skinner and several graduate students shopped the idea to the NDRC and the Navy in 1942, but neither organization initially was interested. Skinner's first funding—$5,000—came from the General Mills Company. A demonstration of the progress so far in March 1943, where the birds now pecked at a screen and the contacts were transmitted electrically to steering mechanisms, resulted in a favorable review by the NDRC and a contract for $25,000 to fund the project to the end of the year.

Later experimentation resulted in a new pneumatic control mechanism, where four air valves released air when the pigeon pecked at the screen. Equal amounts of air were released when the pigeon pecked at the center of the screen. If the bird pecked off center, more air was emitted on one side, displacing a small drum or tambour that connected directly to the control mechanism. Skinner was never able to acquire an actual Pelican bomb or even its technical specifications for use in his experiments, so his group was unable to properly calibrate the signals sent by his working pigeon guidance system. This fundamental disconnect between Skinner and his group and the Pelican group ultimately resulted in the cancellation of Project Pigeon when, in March 1944, Skinner gave one final performance before the NDRC. The meeting, held at the Massachusetts Institute of Technology, involved a live demonstration with a pigeon. The bird pecked "steadily and energetically," in Skinner's words, at a target image moving on an illuminated plate. The pigeon's success, however, couldn't overcome the committee's concern about the integration issues with the Pelican or the fundamentally outlandish nature of the whole project. As Skinner and his sponsor from General Mills, Arthur Hyde, left the meeting, Hyde turned to Skinner and said, "Why don't you go out and get drunk!"

At the time of Project Pigeon's cancellation, the first kamikaze had yet to appear in the Pacific theater. After the first attacks by these suicide aircraft manned by young Japanese pilots later that fall, however, in retrospect the relative "insanity" of Project Pigeon paled in comparison (although perhaps not from the pigeons' perspective). Skinner, in his description of the project published in 1960, could look back with a sense of humor about his years of experimentation, but he also remained adamant that at its heart the concept really could have worked.

A generation of pigeons, if they could be pressed for their thoughts, is probably thankful that it didn't.

In this issue of *Future Force*, we'll look at a number of more successful technological approaches that project combat power extending to the horizon and beyond, or technology that supports the combat systems to do that—from electromagnetic railguns to lasers and the systems that power them.

About the author:

Colin Babb is a contractor serving as the historian for the Office of Naval Research and the managing editor of *Future Force*.

DEVELOPING A HIGH-ENERGY LASER FOR THE NAVY

By Peter Morrison and Dennis Sorenson

The Navy's new Laser Weapon System became the world's first deployed tactical laser weapon aboard USS *Ponce* (AFSB [I] 15) at the end of 2014. Photo by John F. Williams.

We all know the old saying about the unfortunate soul who brought a knife to a gunfight. In the not-too-distant future, we should be able to say we bested our adversaries because we had lasers and they showed up with only a gun. As former Chief of Naval Operations Adm. Gary Roughead said, "I never, ever want to see a Sailor or Marine in a fair fight. I always want them to have the advantage."

Laser weapons will give warfighters options unlike any other system. The same weapon that can be used to identify and then issue a non-lethal warning to an approaching unmanned aerial vehicle can then set a drone ablaze and send it crashing to the ground. With lasers, aim becomes more precise and engagement happens at the speed of light. This goes beyond "fire and forget." This is all about knowing before you fire, knowing as you are firing, providing the warfighter with a graduated response, and then knowing and having evidence that you were effective in your last shot.

The military began experimenting with laser weapons in the late 1970s. Carbon dioxide lasers were initially used to engage airborne and land targets. Although they performed efficiently at megawatt output levels, these systems often were very large, difficult to integrate, costly, and had insufficient target engagement ranges. With the advent of solid-state laser technologies approximately 10 years ago, the Defense Department shifted its focus away from chemical lasers. Although producing considerably less power than chemical lasers, solid-state lasers—which use solid mediums such as glass or crystal rather than a gas or liquid to initiate the lasing process—require only electricity and cooling to operate. The technologies used to develop solid-state laser weapon programs began with the Department of Defense High-Energy Laser Joint Technology Office program called the Robust Electric Laser Initiative, which fostered technology development for several types of lasers in cooperation with industry.

> **Our nation's adversaries are pursuing inexpensive ways to try to restrict our freedom to operate. Spending about $1 per shot of a directed-energy source that never runs out makes more sense than firing costly munitions at a $50,000 threat.**
>
> —Former Chief of Naval Research Rear Adm. Matthew Klunder

High-energy laser weapons cost about $1 per shot to fire—a highly cost-effective approach for countering the threat from unmanned aerial vehicles, which can be manufactured for as little as $50,000 apiece. Defending today's warships with only guns and missiles is a very expensive means of fighting inexpensive threats. A laser would modify this equation in the defender's favor by giving ships what the Navy calls a "deep magazine," reducing the need for replenishing. A ship's existing electrical system can power the laser, and missiles and ammunition can be saved for use against larger and more difficult targets, such as manned aircraft and ships.

Laser weapons complement kinetic weapons currently aboard surface combatants and offer a few specific advantages, such as the ability to:

- Engage with precision without the associated collateral damage of an exploding warhead—and firing depth is limited only by power and cooling
- Offer a measured response, allowing friendly forces first to warn a threat and later to change to a lethal engagement if the threat does not heed the warning
- Complement conventional kinetic-energy weapons such as guns or missiles through accurate laser targeting, ranging, and illumination
- Achieve significant cost savings—against specific threats, the cost per engagement is orders of magnitude less than comparable missile engagements.

Enabling Technologies

Laser technologies have many commercial applications and provide significant benefits to society. Industrial lasers are commonly used to weld, cut, and anneal metal structures to improve durability. Low-power lasers are commonly used for communication or precision distance and angular measurements, such as surveying. Medical uses for lasers are common for surgery and to improve eyesight. Emerging uses of lasers include direct transmission of energy that can be converted into electrical power.

The ability to field high-energy laser systems has been aided by the rapid and substantial improvements of high-power fiber lasers (which are used to form the laser beam) over the past few years by the commercial manufacturing and telecommunications industries. During testing two years ago, the fiber lasers used did not allow a good quality beam to be formed. The latest fiber lasers permit a 10-fold improvement in beam quality and a much increased effective range.

The Office of Naval Research (ONR) maintains a broad portfolio of directed-energy weapon programs comprising shipboard, airborne, and ground-based systems. The way forward toward operational capability is integrating seaworthy and affordable systems through partnerships with the Naval Sea Systems Command, Naval Air Systems Command, Defense Advanced Research Projects Agency, and other services.

Recent Navy investments in laser technology include the ONR-funded demonstration of the first high-energy laser aboard a Navy surface combatant at sea,

Chief of Naval Operations Adm. Jonathan Greenert got a firsthand look at the directed energy Laser Weapon System aboard *Ponce* before the ship deployed to the Arabian Gulf. Photo by MCC Peter D. Lawlor.

as well as demonstrations and investments in the Laser Weapon System and the Mk-38 Tactical Laser System. ONR continues to invest in rapid-fielding initiatives and technical demonstrations, including a successful test of the Laser Weapon System against unmanned aerial systems during exercises off the coast of Southern California in 2012.

These efforts highlight the Navy's ability to prototype, rapidly field, and demonstrate shipboard high-energy laser systems. Widespread use of directed-energy weapons aboard Navy and Marine Corps platforms will continue to be introduced as the technology matures.

What Is the Navy Doing Today?

The focus of the ONR Solid-State Laser program is to address threats such as small suicide boats carrying explosives, intelligence/surveillance/reconnaissance and unmanned aerial systems, or inexpensive armed drones. As power levels increase, the potential exists to defeat more difficult targets—threats aimed at the Navy's surface combatants, amphibious ships, and aircraft carriers. The precision of solid-state lasers and the low cost per shot make these systems an effective and affordable way to counter many potential threats facing deployed naval forces.

Through careful planning, developing key technologies, applying lessons learned from two at-sea demonstrations over the past two years, and leveraging investments made through other Defense Department services and agencies, the U.S. Navy has significantly improved the practicality and capability of shipboard high-energy laser systems. These improvements have resulted in lasers with increased ruggedness, power, and beam quality, which has yielded improvements in laser weapon system overall effectiveness, increased engagement ranges, and decreased time to defeat targets.

In 2014, Naval Sea Systems Command installed a solid-state laser gun aboard USS *Ponce* (AFSB[I] 15) for a deployment in the Arabian Gulf. Operational tests are under way with this weapon, and the knowledge gained will help to develop a prototype system that can be tailored for any ship, from littoral combat ships to destroyers.

"This is a revolutionary capability," said former Chief of Naval Research Rear Adm. Matthew Klunder. "This very affordable technology is going to change the way we fight and save lives."

The 30-kilowatt Laser Weapon System is a capability demonstrator that bundles six commercial fiber lasers. Their beams converge at the target, which is burned or ablated (i.e., the removal of a material's surface). In demonstrations, earlier versions of the system downed several unmanned aerial vehicles and disabled a number of small boats. This team effort brings together the best talent from ONR, Naval Sea Systems Command, Naval Research Laboratory, and Naval Surface Warfare Center Dahlgren Division to make powerful directed-energy weapons a reality. (See page 18 for a more detailed account of how this laser works.)

Lasers of the Future

ONR's Solid-State Laser Technology Maturation (SSL-TM) program is focused on developing the next generation of high-energy laser weapon systems and transitioning that technology to an acquisition program of record. SSL-TM's goal is to design and build an advanced development model prototype solid-state laser weapon (or weapons), install it on a naval vessel, and test it at sea by 2016.

Data regarding accuracy, lethality, and other factors from Ponce's deployment will guide the development of the SSL-TM weapon(s). The program is made possible because of collaboration between ONR, Naval Sea Systems Command's Directed Energy and Electric Weapon Systems Program Office, and Naval Surface Warfare Center Dahlgren Division and the leveraging of contributions from the Department of Defense's High-Energy Laser Joint Technology Office.

Three Navy contractors—Raytheon, Northrop Grumman, and BAE Systems—were awarded contracts to develop different concepts of solid-state laser weapon prototypes between 100—150 kilowatts. As a result of LaWS performance and knowledge gained, new solid-state-based high-energy laser weapon systems with improved effectiveness could be demonstrated in an operational setting on destroyers or littoral combat ships in approximately five years. If all goes well, full-scale deployment of a solid-state laser weapon aboard a ship could become a reality in the 2020s.

Remaining Challenges

In the near term, many challenges remain to develop and operate high-energy laser systems in the maritime environment that are unique to the Navy and Marine Corps. Among these challenges is dealing with the heat generated as power levels increase. A second issue is packing sufficient power on the platform, which will require advanced battery, generator, power conditioning, and hybrid energy technologies. Current laser technologies are approximately 30 percent electrically efficient. Corrosion and contamination of optical windows by shipboard salt spray, dirt, and grime also are technical challenges. In addition, atmospheric turbulence resulting from shifting weather conditions, moisture, and dust is problematic. Turbulence can cause the air over long distances to act like a lens, resulting in the laser beam's diffusing and distorting, which degrades its performance.

Much progress has been made in demonstrating high-energy laser weapon systems in the maritime environment, but there is still much to be done. Additional advances will be required to scale power levels to the hundreds of kilowatts that will make high-energy lasers systems robust, reliable, and affordable. Higher power levels are important for the ability to engage more challenging threats and improve the rate and range at which targets can be engaged.

The programs managed by ONR are addressing these remaining issues while positioning this important warfighting capability toward an acquisition program and eventual deployment with the fleet and force.

About the author:

Peter Morrison is the Office of Naval Research's program officer for the Navy's Solid-State Laser program.

Dennis Sorenson is a contractor with the Office of Naval Research.

The Swarm: Autonomous Boats Take on Navy Missions

By Dr. Robert Brizzolara

What if the Navy could perform some of its toughest and most dangerous missions using a large number of small and inexpensive unmanned surface craft, instead of with a small number of large and very expensive manned platforms? With the cost of Navy ships going up and their numbers going down, the concept of teams of inexpensive unmanned surface vehicles (USVs) becomes not only interesting but increasingly relevant. It would invert the cost asymmetry presented by many threats today. In addition, a team of USVs could be more survivable (since the team could lose a few of its number and still retain its mission effectiveness), less detectable, and more effective for certain missions than individual manned vessels.

These USV teams are enabled by autonomous control, which means the craft are able to drive themselves under remote human supervision rather than operate with the human remotely driving the boat. Controlling large numbers of small boats with the latter method is often not feasible because of the limitations of communications range and operator situational awareness. Autonomous control greatly reduces the bandwidth required to operate the USV, and the amount of cognitive workload on humans. This will allow USVs to operate much farther

away from the control station and allows human supervisors to control multiple USVs.

A distributed system of USVs is compelling because it can be developed using platforms the Navy already has by installing an inexpensive kit that converts these boats from manned to unmanned control. Small craft already are carried on Navy combatants and thus easily transported anywhere in the world in sufficient numbers to perform many useful missions. In addition, USVs could be used with other unmanned platforms to provide increased mission effectiveness. For example, USVs operating in conjunction with unmanned aerial vehicles would provide multidimensional situational awareness.

The USVs were employed in a straits transit scenario that included escort and attack phases. The scenario was conducted in the confined waterspace of the James River near Fort Eustis, Virginia, and is depicted in Figure 1 (see page 16). It included the five autonomous USVs and eight remote-controlled, high-speed maneuverable seaborne target boats, all unmanned. There was a high density of contacts that included the USVs, remote-control boats, a friendly force "high-value" unit, an adversary force contact of interest (a Mark V special operations craft), and various traffic control and support craft. The boats escorted the high-value unit from the southern starting point in the James River through the channel to the north. The contact of interest was the surrogate for the opposition force coming from the east to oppose the high-value unit. The highlights of each phase are described in Figure 1 on page 16.

An August 2014 demostration in Virginia's James River proved that autonomous unmanned surface vessels can perform real-world tasks without a human pilot at the helm.

The Demonstration

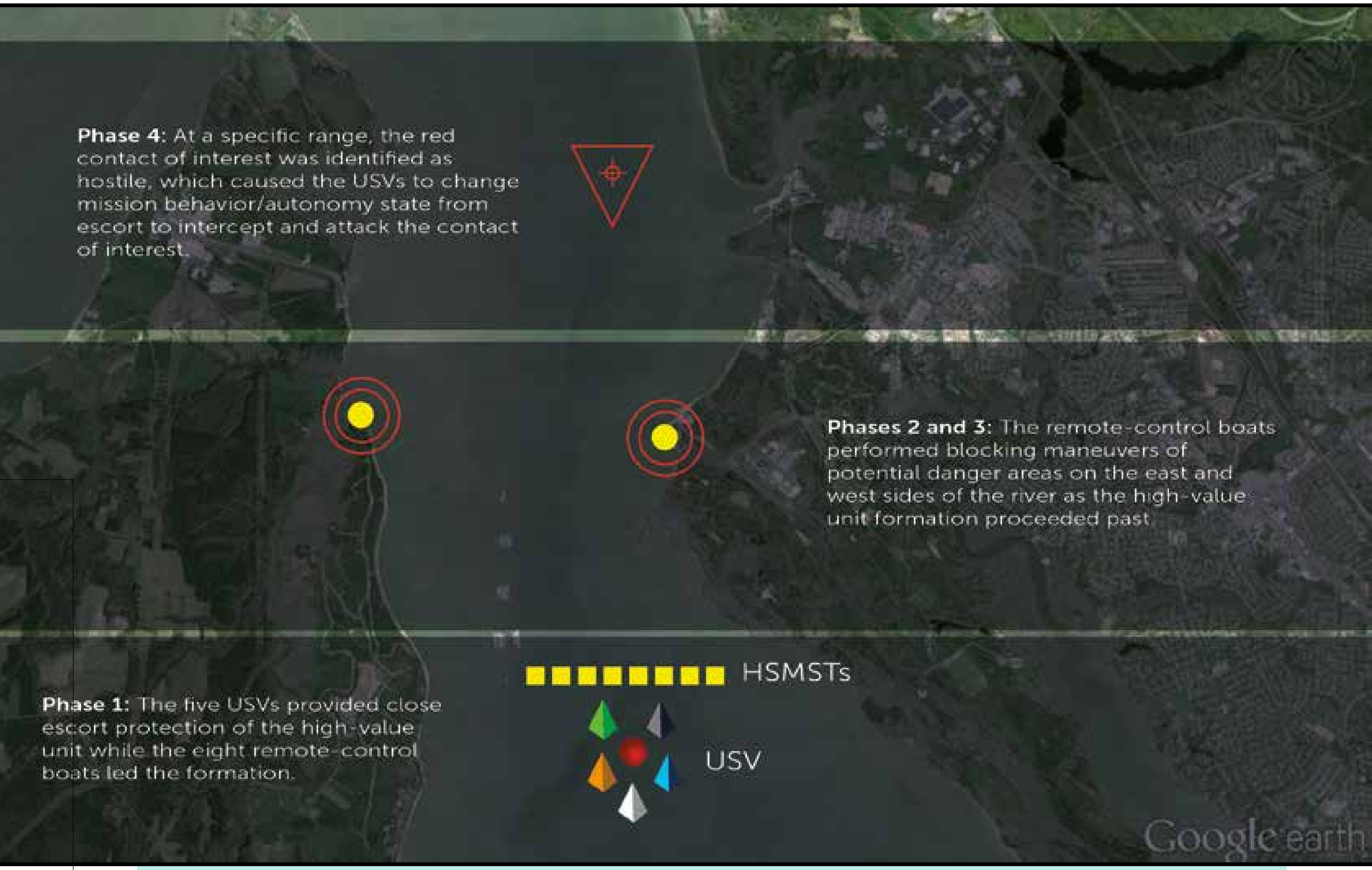
In August 2014, the Office of Naval Research, along with several partner agencies and commands, conducted an autonomous swarm demonstration that employed key technology enablers for USV swarms. The Naval Expeditionary Combatant Command was assigned overall tactical command for the demonstration. The Coast Guard provided traffic control boats and closed sections of the James River for three 30-minute periods per day from 11-14 August. The swarm demonstration technical team included: Spatial Integrated Systems, Inc. (overall execution of demonstration, behavior development, wireless network implementation, and implementation of autonomous control using the Control Architecture for Robotic Agent Command and Sensing, or CARACaS); Daniel Wagner Associates (implementation of the Decentralized and Autonomous Data Fusion System, or DADFS, and radar); Johns Hopkins Applied Physics Laboratory (DADFS); Pennsylvania State University Applied Physics Laboratory (radar processing software); Jet Propulsion Laboratory (developers of CARACaS and behavior development); Naval Surface Warfare Center Carderock Division (four USVs, boat preparation, and demonstration safety); and Naval Surface Warfare Center Dahlgren Division (one USV).

Of the five USVs that participated in the demonstration, two were 11-meter rigid-hull inflatable boats (RHIBs), one was an 11-meter small-unit riverine craft boat, one was a 7-meter RHIB, and one was a 7-meter harbor security boat. The use of different boat types illustrates the versatility of CARACaS. All of these boats are currently in Navy inventory, so existing boats can easily be converted into autonomous USVs.

The Enablers

The demonstration featured two key technical enablers for distributed systems of USVs that are being developed by ONR: the CARACaS autonomous control system, and the DADFS system for fusion of shared situational awareness data. Each USV was equipped with a CARACaS "stack" (a compact processing unit), a commercially available marine radar for perception, and a DADFS unit. CARACaS takes the situational awareness information provided by the radar and DADFS and plans a route to escort the high-value unit or to take an appropriate attack action, depending on the scenario phase, while avoiding obstacles. CARACaS has significant behavior-based autonomous control

Photo by John F. Williams



In Figure 1 above, the Swarm demonstrations' overall scenario is shown. On facing page, the main formation is shown, with a high-value unit being the dark object in upper right. The autonomous boats are the craft immediately around it. In the foreground are the eight remote-controlled boats, or high-speed maneuverable seaborne targets (HSMSTs).

capabilities that were used in the swarm demonstration.

CARACaS has been under development for approximately 11 years. In 2004, ONR initiated a science and technology program to develop autonomous control for USVs performing complex missions in unpredictable and harsh environments. CARACaS advances well beyond the state-of-the art by being able to respond to dynamic situations and organic machine perception. It leverages past NASA investments in artificial intelligence for Mars Rover missions, and has already seen more than 3,500 nautical miles of on-water development, testing, and experimentation time. Functionally, CARACaS consists of two components: a perception engine and a behavior-based control framework that includes a route planner. Both of these were developed by the Jet Propulsion Laboratory.

A key enhancement to CARACaS that enables multiple-USV operations is DADFS, which allows situational awareness sharing and fusion. DADFS is a combination of data fusion algorithms developed by Daniel Wagner Associates and the Johns Hopkins University Applied Physics Laboratory's distributed blackboard system. In an ONR-sponsored project, the DADFS prototype for unmanned vehicles was developed to obtain contact/track data, create a common situational awareness on each vehicle node using collective sensor data, and synchronize the vehicles' situational awareness.

The swarm event was structured to be both a demonstration of the USV autonomous control technology and a science and technology experiment. It demonstrated the use of five autonomous USVs to escort one vessel and attack another. The experimentation was focused on evaluating the performance of the autonomous control system. The system's performance will determine the degree of trust that human operators will have in it—and ultimately its usefulness to warfighters.

One of the challenges associated with this event was that little existed in terms of procedures or processes to evaluate autonomous control systems for USVs, so we largely developed our own methodology for the demonstration. Key quantities were identified and measured, such as the frequency of human intervention necessary, why that intervention was necessary, and

the amount of communications bandwidth used by the control system.

The Results

There were two key aspects of this event that had a positive influence on the results. First, the confined waterspace and high contact density meant there were frequent interactions between the USVs and other craft or keep-out zones (such as shallow water, markers, or buoys) that required the USV to maneuver. This facilitated the collection of a much larger amount of data on the control system's performance than otherwise possible. Second, there were no safety riders aboard the USVs. This was a departure from ONR's usual model for developing autonomous control in which safety riders are on the USVs to take control in case of a malfunction. The lack of safety riders meant that the remote human operator was more likely to take control in a questionable situation. This helped reveal situations in which the remote human lacked trust in the autonomous control system and will facilitate the development of approaches to increase trust.

We found that the predominant causes of the remote human operator taking control of a USV were related to maintaining sufficient buffers around the USVs. For example, the USVs occasionally violated these buffers because of perception issues (false detections that caused the unnecessary maneuvering) or route planning issues (insufficient precision relative to the close quarters in which the USVs were operating). We are pursuing further technology development to decrease both the frequency of human intervention in the operation of the USVs, and the demand for communications bandwidth.

Based on the results of the 2014 autonomous swarm demonstration, autonomous control of at least five USVs for escort and attack missions is feasible. Further technology development will result in a system that engenders increasing levels of trust from human operators and therefore has maximum usefulness to warfighters. There are numerous potential missions for teams of USVs, and those missions and the environments in which they must perform vary greatly in complexity. As trust in the autonomous control system increases, it will be used for more difficult and challenging tasks.

About the author:

Dr. Brizzolara is a program officer with the Sea Platforms and Weapons division at the Office of Naval Research.

NRL AND THE DEVELOPMENT OF THE LASER WEAPON SYSTEM

By Phillip Sprangle, Bahman Hafizi, and Antonio Ting

Ron Flatley, left, high-energy laser area director at the Directed Energy Warfare Office, briefs then-Chief of Naval Research Rear Adm. Matthew Klunder on the Solid-State Laser System's beam director and tracking mount during a tour at Dahlgren, Virginia, in March 2014. The laser is now aboard USS *Ponce* (AFSB[I] 15). Photo by John Joyce.

The development of high-power laser weapons promises to have a profound effect on military missions throughout the services. Laser weapons offer a number of advantages, including agility, speed-of-light delivery, all-electric energy source, low cost per shot, long-range, and the ability to engage multiple targets. In addition, laser weapons can be rapidly adjusted to various target sizes and locations. Previous military lasers were based on chemical processes as the source of laser energy. These lasers have been replaced by solid-state lasers that are far more efficient and do not use dangerous chemicals.

Recent advances in solid-state laser technology have made possible the development of tactical laser weapons. In this article we highlight Naval Research Laboratory (NRL) scientists' role in developing the concepts that form the basis of the Navy's Laser Weapon System (LaWS), a technology demonstrator that employs solid-state fiber lasers. LaWS provides defense against airborne drones or small boats using a number of incoherently combined fiber lasers that can destroy targets or (at low power) warn or cripple targets' sensors. Laser weapons such as LaWS will complement other missile- and kinetic-based defense systems rather than replace them.

LaWS employs six fiber lasers, which instead of cohering into a single beam they merge at the target (hence, they combine "incoherently"). The simplicity of this approach is what has allowed the Navy to advance LaWS rapidly and cheaply to the point that it has been deployed in the Arabian Gulf for at-sea tests.

The Naval Research Laboratory's Role

In 2005, NRL scientists were the first to propose, analyze, and simulate the use of incoherently combined, high-power fiber lasers as the architecture for LaWS.[1] The patented NRL laser beam-combining architecture is considered one of the most promising approaches for developing tactical laser weapons.[2] Shortly after the initial analysis and simulation of the concept, NRL scientists and team members from the Naval Surface Warfare Center carried out the first long-range field experiments.

Fiber lasers are well suited for incoherent combining and high-power, long-range directed energy applications.[3] Each of the six lasers' steering mirrors is individually controlled to form the beam director and direct each beam to converge on the target. The incoherently combined laser system is relatively simple, efficient, compact, robust, low maintenance, and potentially long lasting.

It is important to minimize lateral spreading of the laser beams; this allows for a higher concentration of energy on the target. To limit lateral spreading over the propagation range, the individual spot size (radius) of the beams must be large enough at the source and the lasers must have good optical quality. The optical quality is an important factor in determining the propagation range, and single-mode operation of the fiber laser is highly desirable..

Fiber lasers are compact. For example, a 1-kilowatt, laser module occupies a volume less than a half a cubic foot (excluding power supply), weighs about 20 pounds, and has an operating lifetime in excess of 10,000 hours each. Because of their high operating wall-plug efficiency these lasers require only moderate cooling (a few gallons of water per minute per kilowatt).

For high-optical-quality lasers propagating over extended distances the effects of atmospheric turbulence will usually dominate over diffraction. For poor-optical-quality lasers, however, turbulence contributes significantly less to beam spreading.

In general turbulence degrades the quality of optical images. A common example of this is the scintillation of light when a distant object is observed (such as the twinkling of a star). Adaptive optics techniques have been developed over the past half century to mitigate the effects of turbulence in astronomical telescopes and, more recently, in directed energy systems. Adaptive optics can compensate for some turbulence but not all effects. Adaptive-optics techniques can enhance propagation efficiency for single-mode lasers, but it will have little effect with multimode lasers.

Tip-tilt correction is a simplified method for adaptive optics that can be applied to the individual steering mirrors to minimize the overall combined laser spot size on target. Tip-tilt correction redirects the centroids of the individual laser beams to reduce the effects of wander due to turbulence. This is accomplished by monitoring the laser intensity on target and redirecting the individual steering mirrors. Laser beam centroid wander depends on the size of the turbulence eddies. Eddies that are large compared to the beam diameter cause the beam centroid to be deflected and wander in time due to lateral air flow. Small eddies, on the other hand, cause the beam's short-term spot size to spread about the centroid. The observed long-time averaged spot size is a combination of these two effects.

The Navy's new Laser Weapon System, which recently deployed abroad a ship for the first time, began life as a science and technology effort with the Naval Research Laboratory.

Incoherent Combining of Fiber Lasers

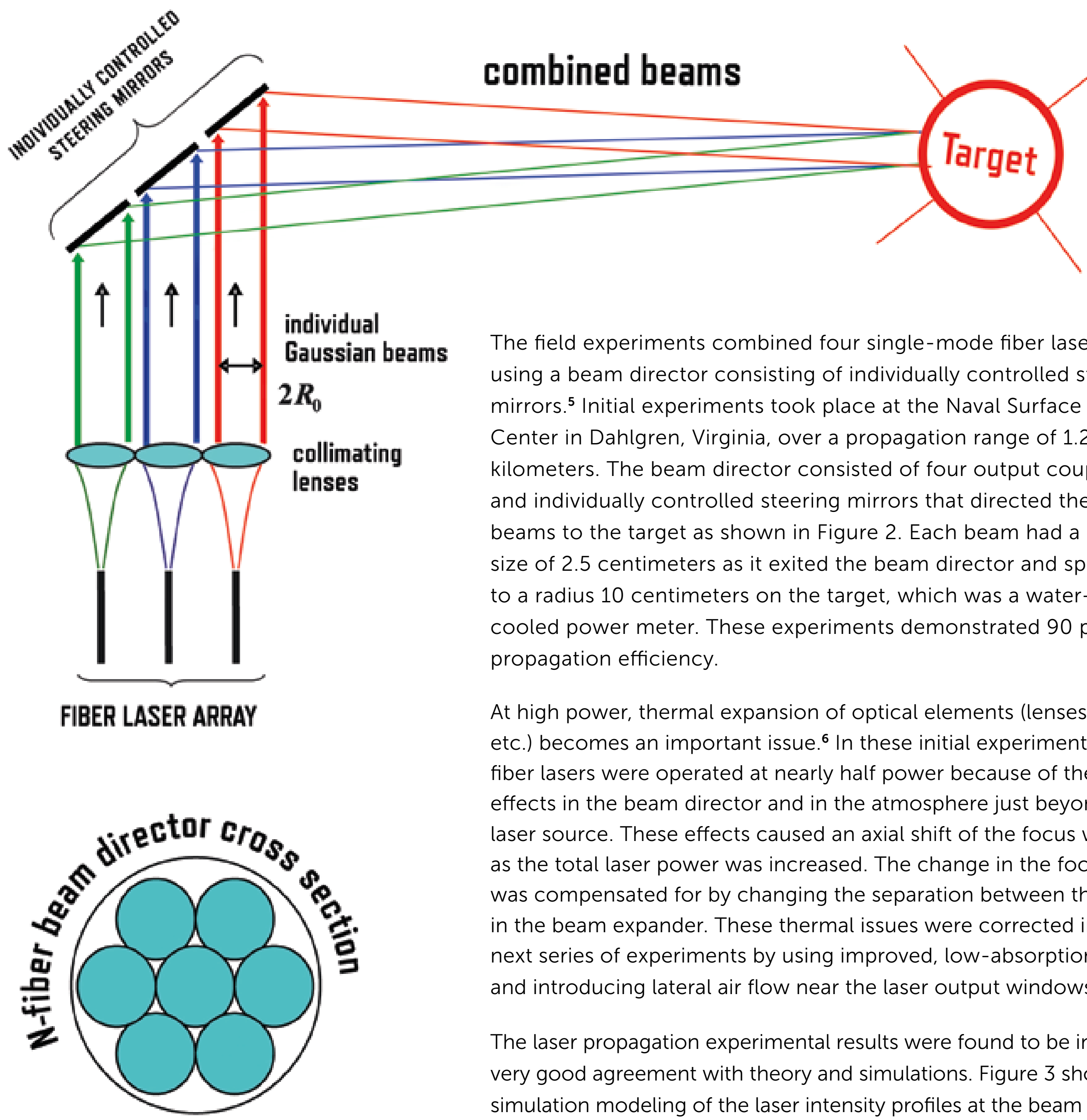
The essence of incoherent beam combining is illustrated in Figure 1, which depicts a hexagonal array of seven fiber lasers combined with a beam director of individually-controlled steering mirrors. The individual lasers have an initial cross section selected so that lateral spreading is not significant over the propagation distance. Typically, atmospheric turbulence will result in far more lateral beam spreading. Incoherent beam combining is fundamentally simpler than other beam combining techniques (such as spectral or coherent beam combining, where several beams are combined within the laser module). This approach does not require optical phase locking of the lasers, and can be readily scaled up in power to a compact and reliable directed energy system.

The physical processes limiting the propagation range of high-power laser beams to the target include diffraction, molecular/aerosol scattering and absorption, turbulence, mechanical jitter, and thermal blooming.[4]

Fiber Laser Experiments

Some of the objectives of the experiments NRL conducted were to validate the laser propagation models and to demonstrate the incoherent beam combining concept at long range, as well as, in particular, to more precisely characterize the laser beam wander and spreading in a turbulent atmosphere.

FIGURE 1: HOW NRL'S INCOHERENT FIBER LASER WORKS



The field experiments combined four single-mode fiber lasers using a beam director consisting of individually controlled steering mirrors.[5] Initial experiments took place at the Naval Surface Warfare Center in Dahlgren, Virginia, over a propagation range of 1.2 kilometers. The beam director consisted of four output couplers and individually controlled steering mirrors that directed the four beams to the target as shown in Figure 2. Each beam had a spot size of 2.5 centimeters as it exited the beam director and spread to a radius 10 centimeters on the target, which was a water-cooled power meter. These experiments demonstrated 90 percent propagation efficiency.

At high power, thermal expansion of optical elements (lenses, mirrors, etc.) becomes an important issue.[6] In these initial experiments the fiber lasers were operated at nearly half power because of thermal effects in the beam director and in the atmosphere just beyond the laser source. These effects caused an axial shift of the focus with time as the total laser power was increased. The change in the focal length was compensated for by changing the separation between the lenses in the beam expander. These thermal issues were corrected in the next series of experiments by using improved, low-absorption optics and introducing lateral air flow near the laser output windows.

The laser propagation experimental results were found to be in very good agreement with theory and simulations. Figure 3 shows simulation modeling of the laser intensity profiles at the beam director (panel a), the combined beams at the target in simulation (panel b), and in experiment (panel c). The next series of NRL field experiments were

ENDNOTES

1 "Incoherent Combining of High-Power Fiber Lasers for Long Range DE Applications," P. Sprangle, *2006 Solid State and Diode Laser Technology Review* (June 2006); "Incoherent Combining of High-Power Fiber Lasers for Long-Range Directed Energy Applications," P. Sprangle, J. Peñano, A. Ting, and B. Hafizi, NRL Memorandum Report, NRL/MR/6790--06-8963 (2006); "Incoherent Combining of High-Power Fiber Lasers for Directed Energy Applications," P. Sprangle, A. Ting, J. Peñano, R. Fischer, and B. Hafizi, NRL Memorandum Report, NRL/MR/6790--08-9096 (2008).

2 "Apparatus for Incoherent Combining of High-Power Lasers for Long-Range Directed-Energy Applications," P. Sprangle, J. Peñano, B. Hafizi, A. Ting, and R. Fischer, U.S. Patent No. US 7,970,040.

3 "Incoherent Combining and Atmospheric Propagation of High-Power Fiber Lasers for Directed-Energy Applications," P. Sprangle, A. Ting, J. Peñano ,R. Fischer, and B. Hafizi, *IEEE Journal of Quantum Electronics* 45, 1-2 (2009); "High-Power Fiber Lasers for Directed-Energy Applications," P. Sprangle, A. Ting, J. Peñano, R. Fischer, and B. Hafizi, *2008 NRL Review* (2009), p. 89.

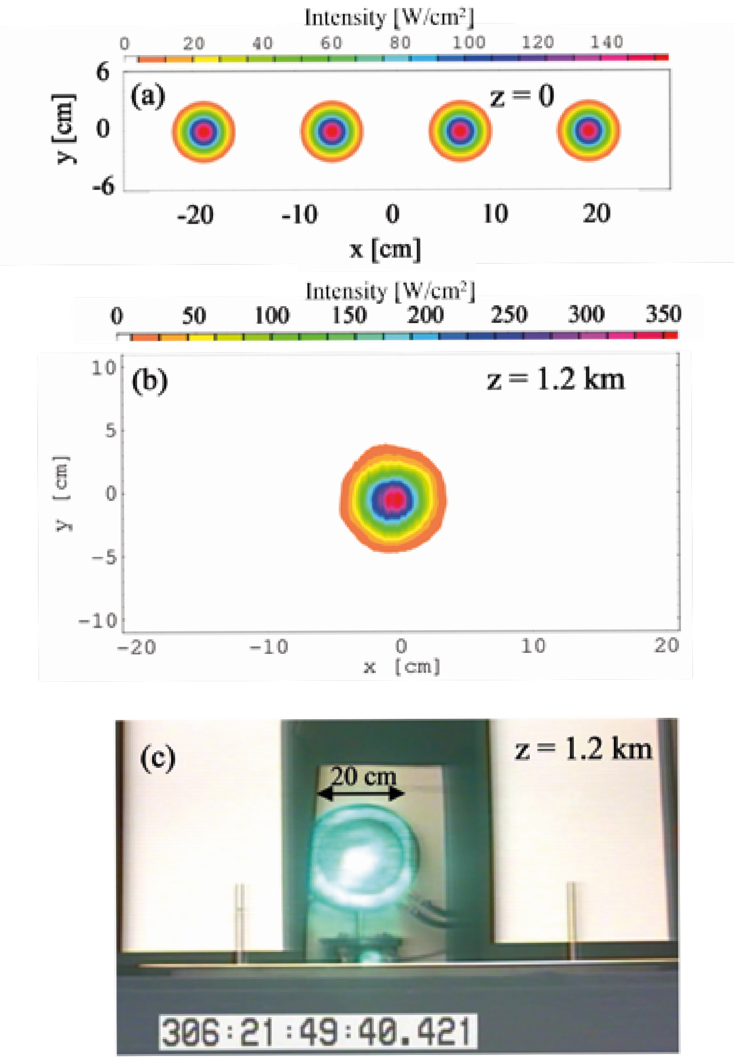


Figure 2 shows a two-second time-averaged transverse intensity profile of laser beams at (a) the source and (b) incoherently combined on target at a range of 1.2 kilometers. The individual initial spot size is 2.5 centimeters and the combined spot size on target is 10 centimeters. (c) A camera image of four beams incoherently combined on target at a range of 1.2 km.

performed in 2009 at an increased propagation range and tip-tilt control of the incoherently combined laser beams was employed. Immediately following these successful experiments, a Naval Sea Systems Command lethality/propagation program was initiated at Dahlgren using six fiber lasers, each having a continuous power of 5 kilowatts, in conjunction with a joint Pennsylvania State University/Naval Surface Warfare Center Crane Division lethality and propagation program using two 10-kilowatt and 5-kilowatt fiber lasers.

The ground-breaking NRL laser propagation experiments provided critical basic information addressing the issues associated with incoherently combined, high-power, single-mode fiber lasers. These experiments led to the Navy's first LaWS. In late 2014, LaWS deployed aboard USS *Ponce* (AFSB[I] 15) as part of the Office of Naval Research-funded Quick Reaction Capability program to undergo at-sea testing in the Arabian Gulf. To fully realize the potential capabilities of a laser weapon such LaWS for long-range and high, continuous power levels (more than 100 kilowatts), science and technology issues such as adaptive optics for propagation in maritime deep turbulence, thermal blooming, and thermal management in the director optics will need to be addressed.

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The authors would like to acknowledge that the theory, modeling, and experimental research support to demonstrate proof of concept on the incoherent laser beam combining architecture was provided by the Naval Research Laboratory, Office of Naval Research, and High-Energy Laser Joint Technology Office.

4 "Optimum Wavelength and Power for Efficient Laser Propagation in Various Atmospheric Environments," P. Sprangle, J. Peñano, and B. Hafizi, *Journal of Directed Energy* 2, 71 (2006).

5 "Incoherent Combining and Atmospheric Propagation of High-Power Fiber Lasers for Directed-Energy Applications," P. Sprangle, A. Ting, J. Peñano ,R. Fischer, and B. Hafizi, *IEEE Journal of Quantum Electronics* 45, 1-2 (2009); "High-Power Fiber Lasers for Directed-Energy Applications," P. Sprangle, A. Ting, J. Peñano, R. Fischer, and B. Hafizi, *2008 NRL Review* (2009), p. 89.

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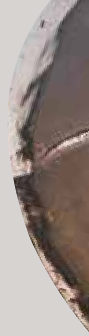
The All-Electric Future is Closer Than You Think

By Stephen P. Markle



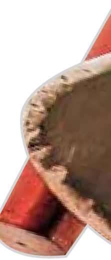
The offensive and defensive capabilities of today's U.S. warships are unmatched across the globe, and this power enables the Navy and Marine Corps' credible forward presence. What about in the future? As those who may challenge the United States continue their drive to match our capability, the Navy is poised to field revolutionary high-power weapons and sensors. Technology advancements and innovative thinking are bringing to reality systems that seemed like science fiction only a few years ago. Previously only seen in futuristic movies, shipboard lasers, railguns, high-energy radars, and microwave systems are currently under development with plans for fleet introduction in the next several years.

Power in today's warships is focused largely toward driving propulsion. Research is finding ways to change that equation for the energy-hungry fleet of tomorrow.

Each of these directed-energy weapons and sensors is electrically powered, which places unprecedented demands on shipboard energy systems. This energy revolution at sea is equivalent to the introduction of steam power in the 19th century or the rise of the digital computer, nuclear power, and Aegis combat system in the 20th century. To achieve this level of change, the naval science and technology community must create the necessary shipboard energy conversion, energy storage and control, and cooling infrastructure to bring the vision to reality. The future truly will be one where we can shift power from propulsion to sensors and weapons in the blink of an eye.

A Vision for Future Power Systems

To understand what a high-powered electric future may mean, it is helpful to look back at the steam-powered past. With some exceptions, since the advent of steam propulsion most U.S. naval vessels have had segregated propulsion and electric power plants—meaning that the main power-producing system (steam, gas-turbine, etc.) drives only the propulsion of the ship, and everything else (lighting, ventilation, computers, etc.) is powered by subsidiary (and usually less powerful) generating units. Today's widely used gas turbines have benefits—most notably higher power density and reduced maintenance—but from an electrical standpoint they have somewhat limited the flexibility to incorporate higher-powered electric weapons and sensors. Current surface combatants have all-time-high levels of installed power, yet the majority of that power is directed only to the propulsion system. Because of propulsion and electric plant segregation, none of that propulsion power can be shifted to any other part of the ship. An "all-electric" ship, in contrast, has a single, integrated electric plant for all electrical systems, including propulsion—allowing power to be shifted throughout the ship on an as-needed basis.



The Electric Ships Office (PMS 320) in Program Executive Office (PEO) Ships coordinated with the naval science, technology, and engineering communities to develop and execute the Naval Power Systems Technology Development Roadmap (NPS TDR): Naval power systems must provide ships and systems that consume large quantities of energy, such as directed-energy weapons, the right power and energy quality of service, where and when it is needed. In addition, naval power systems must extract as much energy as economically achievable from every drop of fuel that is loaded aboard.

Naval power systems reside at the busy intersection of directed-energy weapons and high-powered sensors and ship systems. This interface is very important and involves coordinating a number of important elements: electric power, lubrication, cooling fluids, and information (controls, safety, and combat systems). Interface management is an essential part of any complex

Photo by MCSA Theodore Quintana

engineering project and is more than just making sure the bolt holes line up.

Historically, naval power systems have provided energy in various forms to enable warfighters to accomplish their missions. Standard design margins and lifecycle growth allowances were sufficient to ensure operation over ships' entire service lives. The introduction of directed-energy weapons and high-powered sensors is forcing an important dialogue to ensure the right balance is struck between what ships provide and what is delivered with mission systems. Ships cannot support every mission system coming aboard with a bevy of auxiliary equipment, and mission systems cannot compromise on their warfighting requirements.

To the uninitiated, technology development for naval power systems could be overwhelming because of a system's depth and breadth, which includes generating, distributing, and converting electricity; providing circuit protection and controls; and delivering power to end users. The NPS TDR outlines the way ahead for electric power systems and informs stakeholders of current and anticipated Navy investments in research and development, since they are the ones who will be required to make these revolutionary weapon and sensor systems a reality. The NPS TDR is updated every two years to provide revised predictions as legacy challenges are answered, new ones are identified, and adjustments are made to the Navy's 30-year shipbuilding plan. The next iteration of the NPS TDR is planned for early 2015.

Technology Pipeline

A number of complementary technology developments are being established to address shortfalls in existing ship systems and to protect Sailors and their ships while these emerging high-powered mission systems are operating.

As mission systems' operational requirements become well defined through developments and demonstrations, updated ship systems requirements also are being identified. Since many of the new sensors and weapons favor medium-voltage direct-current (MVDC) power for functionality and the need to store and release energy quickly (such as that required for lasers, railguns, or the Electromagnetic Aircraft Launching System on aircraft carriers), one of the main approaches being considered for the electric power system is to adopt an MVDC distribution architecture.

While MVDC has a number of potential benefits for future ships, the technology requires significant development and integration before it can be fielded on a warship. The U.S. Navy and the U.K. Royal Navy share this power system vision and are collaborating on the Advanced Electric Power and Propulsion Systems Development Project. The goals are to integrate next-generation weapons and sensors, enhance survivability, lower acquisition and operating costs, and ensure the safety of future naval platforms. The Defense Department and Ministry of Defence are conducting complementary research, design, modeling, and simulation of electric power system architectures focusing on MVDC. In addition, the partners intend to build and test power system components and prototypes.

MR1 Matthew Travis stands watch in USS *Mustin's* (DDG 89) main engineering control room. In the electric surface ships of the future, power will be a central resource that can be directed to any system depending upon need. Photo by MC2 Declan Barnes.

Focused research and development is under way to tackle some of the challenges presented by shipboard use of MVDC. In MVDC applications, the Navy will need to develop circuit interruption and protection relay systems that are power dense, address combat faults, and can respond in milliseconds (approximately 1-10). Existing circuit protection technologies are inadequate, requiring new advanced circuit protection to replace slow-acting circuit breakers and protective relays. These solid-state components are being developed through the Office of Naval Research (ONR) to increase available mission power, reduce the energy of an arc fault (a high-power discharge of electricity between two conductors) and its resulting impact on equipment and personnel, and boost the electric system power density. ONR research includes component- and system-level architectures, as well as technological leaps forward through the use of advanced materials such as silicon carbide. These technologies enable faster response times, higher frequency operation (hence smaller footprints), and higher allowable operating temperatures that potentially could reduce thermal management needs.

Multifunction energy storage is being developed to accommodate the pulse load requirements of mission systems and their resultant effects on ship power systems. This ONR-developed capability will yield components and methods to enable high-density, high-cycle-rate, and megawatt-scale energy storage systems. To accommodate the power needs of railguns, for instance, enormous amounts of energy will need to be released (or pulsed) and then recharged (or cycled) several times a minute. These power systems will incorporate safety and containment capabilities, operate with advanced controls, and serve ships with pulse load mission systems. In addition, multifunction energy storage enables alternative electric plant configurations that will improve operating efficiency and save fuel by augmenting power delivered to the mission systems, and allowing the ship's generator sets to operate in ranges closer to their optimal fuel efficiency settings.

All of these systems, including the advanced weapons and sensors, MVDC architecture, advanced circuit protection, multifunction energy storage, and supporting ship systems such as cooling and information systems, will operate under the umbrella of an advanced control system that will manage power from multiple and shared energy generation and storage devices. This planned capability will manage all required resources to anticipate and pre-position power where it is needed. Using this more autonomous approach, operators will provide mission requirements to the control system that will determine optimal configurations to support mission system requirements and manage the allocation and flow of power, as well as the support from other ship systems.

Integration

New weapons and technologies soon will be mature enough to be integrated onto U.S. warships. Roadmaps are being developed to chart the course of these developments, providing insight into what could be available and when. So how do these new capabilities get to sea? This effort requires numerous experts to follow the roadmap, engineer necessary changes, and implement new systems.

To provide this direction, a senior leadership-level Combat Power and Energy System Overarching Integrated Project Team (CPES OIPT), co-chaired by PEO Ships and the Naval Systems Engineering Directorate, has been chartered by Commander, Naval Sea Systems Command, to develop and endorse common solutions to enable shared asset utilization and to support advanced weapons and sensors.

PEO Ships has the critical role of incorporating the common solutions set into the design and construction of future ships. For future mission systems, affordability requires stakeholder collaboration to define acceptable solutions to achieve common capability goals. These solutions will require optimizing multiple interconnected systems at the ship level instead of at the system level, leading to an overall optimized design at the ship level. This approach to integrating mission loads and power systems will lead to the maximum capability at the right cost.

The CPES OIPT near-term focus is to address the ship integration requirements of the following systems: integrated power systems; lasers (especially solid-state lasers); electromagnetic railgun; high-power microwave weapons; advanced radar systems; and Surface Electronic Warfare Improvement Program, Block III.

The CPES OIPT's near-term goal is to facilitate development of an "energy magazine" that can be used to incorporate advanced weapon and sensor systems in ships under construction or as a back-fit option for existing ships. This includes identifying those actions needed to develop, test, and install energy magazines in selected ship classes. An energy magazine supplies the energy management, controls, and cooling required to service these new high-power and -energy mission systems. The functionality provided by energy magazines could be incorporated into future ship designs. The CPES OIPT also is focusing on identifying and coordinating those actions needed to validate specific technology products. This includes analyses, development goals, and tests required to maturate the potential technology products into an appropriate demonstration(s) in the 2018-2021 timeframe.

Conclusion

Future naval power projection will include advanced mission systems such as directed-energy weapons. Surface combatants of the future will have highly complex, integrated naval power systems that must strike a balance between performance, cost, and lifecycle requirements. The Navy is pursuing technology development and testing in a deliberate fashion as outlined in the NPS TDR. MVDC architectures are being considered for future ships, and there is a strong focus on integrating directed-energy weapons. A CPES OIPT has been established to facilitate coordination and integration of all these developments.

Future naval power projection and power systems are inextricably linked. To make both visions a reality, the Navy must continue mission systems and sensors development—but also must make commensurate investments in power system and auxiliary systems research and development.

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Stephen Markle is the director of the Electric Ships Office (PMS 320) in Program Executive Office Ships. In this capacity he is responsible for developing electric power and propulsion systems for the Navy's fleet. He also is responsible for stewardship of the living Naval Power Systems Technology Development Roadmap to guide intelligent technology investment toward meeting current and future fleet warfighting capability needs.

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Thirty Years of the LCAC

By Jeffrey Prater

After three decades of service, the landing craft air cushion is still going strong.

One of the reasons the U.S. Navy is the most powerful navy in the world is because of its ability to fulfill the core mission area of power projection. At the Naval Surface Warfare Center Panama City Division (NSWC PCD), the core mission means landing Marines and their equipment ashore aboard landing craft air cushion (LCAC) vehicles. The LCAC celebrated its 30th anniversary in 2014. On 29 May 1984, as reported in the Naval Coastal Systems Center's newsletter, *The Underseer*, "The first production unit of the Landing Craft Air Cushion vehicle was being offloaded at its berth in the high bay area of Building 319 after a journey by barge from Bell Aerospace Textron New Orleans where it was built under contract to the Naval Sea Command."

Hovercraft technology first came to the warfare center in November 1964 when the Bell-Westland SR-N5, an air-cushion vehicle combining the efforts of Bell Aerosystems USA and the U.K.'s Westland Aircraft Limited, arrived in the waters off Panama City. The Underseer reported, "It appears to be a cabin cruiser on rubber pontoons, but in fact is a versatile craft with a wide range of applications." Subsequent test craft included a surface effect ship in 1972, the assault craft vehicle *Voyageur* in 1975, the Landing Assault Craft Vehicle-30 in 1977, and the LCAC prototypes *Jeff A* and *B* in 1977 and 1979, respectively.

When the technology used in the LCAC-1 was introduced, it was considered the first significant improvement in waterborne landing craft since World War II—able to transport troops, weapons, and equipment at speeds greater than 40 knots from support ships over the horizon to landing points beyond the beach. Because of its unique amphibious capabilities, it can land on 70 percent of the world's beaches, which was a four-to-one improvement over conventional landing craft of the day. According to Dave Vickers, head of the Expeditionary Systems division for NSWC PCD, "The LCAC represented an evolutionary leap in the capabilities of landing craft to access more beaches, landing troops ashore more quickly, where the enemy is not established."

The first LCAC detachment, consisting of three craft from Assault Craft Unit (ACU) 5, deployed to the Western Pacific

Photo by MC2 Corbin J. Shay

Photo by MC2 Christopher Lindahl

in June 1987. ACU 4 conducted several highly successful operations providing further proof of the LCAC's potential, including cold weather testing at the Air Force's climate-controlled hangar at Eglin Air Force Base, Florida, in the summer of 1987. These tests demonstrated that the LCAC is able to operate in a temperature range of -30 to 160 degrees Fahrenheit (below deck). In early November 1987, ACU 4 changed homeports from Panama City, Florida, to Naval Amphibious Base Little Creek, Virginia, where they placed three LCACs in operation.

Over the next 15 years, 91 craft were delivered to the U.S. Navy, of which 81 are still in operation today. The original craft were capable of carrying a 60-short-ton payload with an overload payload capacity of 75 short tons. More than 90 percent of the Marine Air-Ground Task Force equipment is too heavy for vertical lift, and LCACs are the only craft with the speed and range to deliver the surface component of a Marine expeditionary brigade from over the horizon in one period of darkness.

LCACs were designed to last 20 years, but with a service life extension program upgrade their lifecycles have been extended another 10 years. The upgrade refurbishes all rotating machinery, includes a complete command, control, communications, computers, and navigation replacement, and adds enhanced engines and a deep skirt system, which increased the cushion from 5 to 7 feet. These upgrades have extended the expected service life of the LCAC program to approximately 2028.

Through the years, LCACs have been deployed around the world and taken part in numerous amphibious operations. In 1990-91, LCACs were deployed to the Arabian Gulf in support of Operations Desert Shield and Desert Storm. In 1993, LCACs were used to bring Marines and equipment ashore in support of United Nations actions in Somalia. In 1994, LCACs took part in Operation Provide Comfort in Haiti. More recently, LCACs have provided humanitarian assistance and disaster relief after earthquakes in Haiti and Japan, Hurricane Sandy, and Typhoon Haiyan in the Philippines. To date, LCACs have logged more than 130,000 operational hours of service.

On the horizon is the next-generation LCAC, the Ship-to-Shore Connector (SSC). The research and development for the SSC is complete, and the new design is under contract. Expected arrival in Panama City is 2017, and then initial testing and evaluation will begin. As the first LCACs retire, the SSC will begin to enter the fleet with an initial operational capability projected in 2020. The SSC maintains a similar footprint as the LCAC and will operate from existing and planned amphibious well-deck ships. The SSC increases the nonoverload lift capability from 60 to 74 short tons, and it can carry this larger payload across a broader operational envelope (such as operating in higher sea states). SSC also is expected to have reduced fuel consumption and maintenance needs.

For 30 years, LCACs have been supported by the engineers, logisticians, and technicians at NSWC PCD in its role as the platform's in-service engineering agent; NSWC Carderock Division Philadelphia in its role servicing gas turbine engines and drive trains; and the Space and Naval Warfare Systems Command in its role as the agent for communications. This support team and the men and women in uniform serving in ACU 4 and 5 and Naval Beach Unit 7 have enabled the Navy/Marine Corps team to successfully conduct operations in the littorals. Whether those operations involve combat or humanitarian assistance or something in between, LCACs have set the U.S. Navy apart from the rest of the world with the ability to deploy and sustain expeditionary forces ashore.

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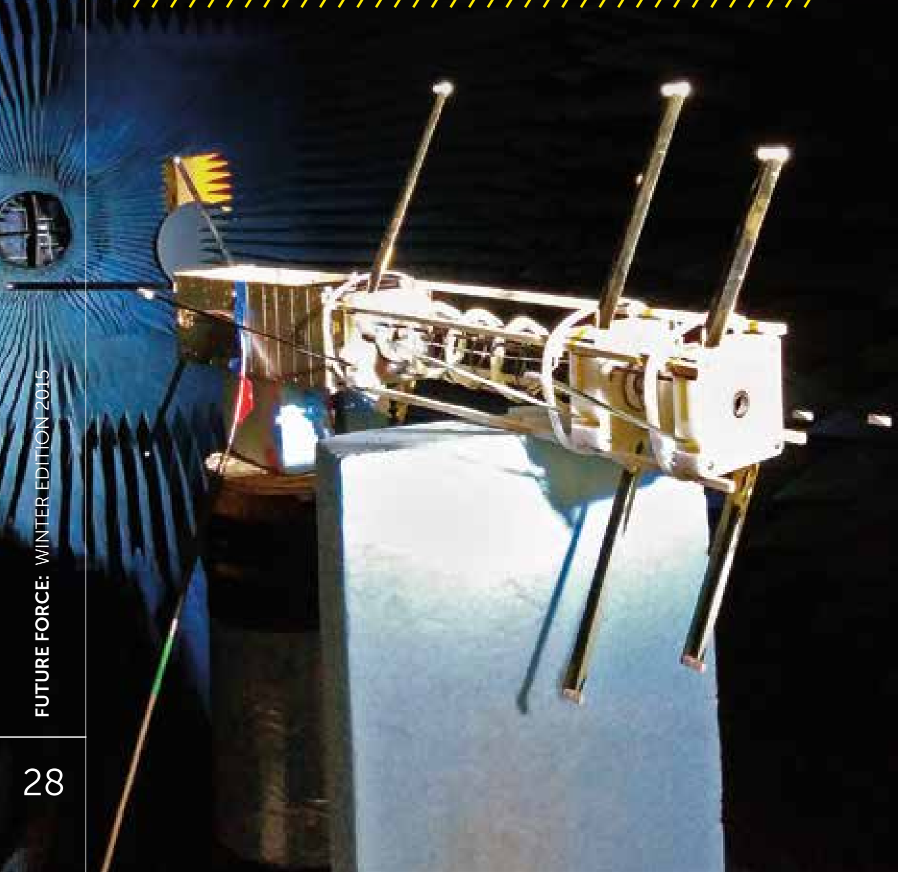
NANOSATELLITES:

BIG POSSIBILITIES IN SMALL PACKAGES

By Austin Mroczek and Patric Petrie

Phones are getting larger, but satellites are getting smaller—and proving to be a cost-effective and practical way to get sensors, comms, and other hardware into space for scientists as well as warfighters.



Nanosatellites are an emerging low-cost space technology being developed by Space and Naval Warfare Systems Center (SSC) Pacific and other organizations in the Navy. The Naval Research Laboratory developed some of the first military nanosatellites, and it continues to develop technologies such as miniature solid-propellant thrusters, environmental monitoring sensors, and automated satellite operations software. The Naval Academy and Naval Postgraduate School also are heavily involved in developing nanosatellites.

Nanosatellites are less than a foot long and weigh less than 25 pounds. A common form factor is the CubeSat, which was developed as a low-cost means to teach university students how to develop space systems. CubeSats were originally 10 centimeters on each side and weighed less than a kilogram. That size was later called one unit or "1U," and larger sizes were developed. Now 3U is common, and many organizations are building 6U or larger satellites.

Nanosatellites are launched into orbit when a larger satellite mission has spare room, similar to riding on a space-available airline flight. Once the primary space mission separates from the launch vehicle, the nanosatellites are deployed from a spring-loaded canister. More than 100 were launched in both 2013 and 2014, and hundreds more nanosats are in development by academic, commercial, and military organizations.

A number of factors limit nanosatellite capabilities. Smaller size means less power, which means less time to operate sensors or communication links. When communication links are available, they are generally very low bandwidth. Hitchhiking into space means nanosatellites don't always get their preferred orbit, which is critical for certain space missions. Few nanosatellites have propellant to keep them in their orbits or to maintain their spacing with other satellites. These factors limited the capability of early nanosatellites.

Nanosatellites nonetheless make up for limited capabilities in a number of ways. Entirely new missions can be developed for less than $10 million, and copies can be produced and launched for less than $1 million each (rather than for tens or hundreds of millions for "full-size" satellites). The development and production timeline is measured in months instead of years. In addition, nanosatellites provide strength in numbers, enabling dozens or even hundreds of satellites to be launched quickly and at low cost.

Kyle Lackinger, an Space and Naval Warfare Systems Center Pacific electrical engineer, runs tests on the Integrated Communications Extension Capability satellite system. Photo by Alan Antczak.

Ongoing science and technology investments have steadily improved nanosatellite capabilities. Program Executive Office (PEO) Space Systems invested Small Business Innovation Research funds in a number of enabling technologies. A high-gain, ultra-high-frequency antenna stored in the satellite then pops out to nearly double the craft's size, providing improved communications. Software-defined radio and encryption technology enables secure communications. New star-tracking technology gives nanosatellites precise information about their positions in space, which is critical for remote sensing. SSC Pacific is developing a low-power optical communications technique based on previous airborne work by the Naval Research Laboratory. SSC Atlantic is developing a platform to host the optical communications payload.

Recent work has led to the development of nanosatellites to demonstrate the military capabilities. The Vector Joint Capability Technology Demonstration launched two satellites to orbit in November 2013 to test advanced communications capabilities. The system is currently being evaluated by a combatant command for potential operational use.

PEO Space Systems, with support from SSC Pacific, is developing a 3U CubeSat called the Integrated Communications Extension Capability, or ICE-Cap. After launch in 2015, the system will demonstrate the ability to communicate through the Mobile User Objective System to send data directly to users on secure networks. ICE-Cap also will show the ability to relay communications from a user near the North Pole to another user halfway around the world.

Commercial companies also have been quick to adopt nanosatellite technology. In the past year, one company has launched more than 40 nanosatellites that provide three-to-five-meter-resolution imagery. The company plans to launch more than 200 satellites total with the goal of taking a picture of every point on the earth once a day. The company builds a new generation of satellite about every eight weeks and at peak production builds two per day.

Nanosatellites can't replace every large satellite, but they are quickly becoming more capable. Future nanosatellites will provide capabilities in communications, intelligence, surveillance, reconnaissance, environmental monitoring, and other missions. Nanosatellites can provide unique access to areas that undersea or airborne platforms cannot. Adversaries can hide from a handful of satellites, but dozens of satellites are nearly impossible to avoid. The naval forces need to adapt to their use by others—and adopt them for their own.

About the authors:

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Patric Petrie is the lead staff writer for SSC Pacific.

TOMORROW'S TECH

►► By Roger Ellis

THE ELECTROMAGNETIC RAILGUN IS GOING TO SEA

Chief of Naval Operations Adm. Jonathan Greenert called the electromagnetic railgun "our future surface weapon" during a September 2014 tour of the Electromagnetic Launch Facility at the Naval Surface Warfare Center in Dahlgren, Virginia. Greenert's comment reflects a vision of and an enthusiasm for the future role of the railgun aboard Navy surface combatants. A railgun weapon system can launch 35-pound, precision-guided projectiles at Mach 6 to engage close-in air threats or targets up to 110 nautical miles away. Millions of amps of current pulsed to the railgun breech over a few milliseconds generate an electromagnetic force that replaces the chemical propellants traditionally used to fire projectiles.

The sheer force (i.e., kinetic energy) of the guided projectile's impact will damage or kill the targets. Firing farther and faster than any preceding gun, the electromagnetic railgun will fulfill the Navy's desire for an affordable long-range weapon capable of many missions.

In 2005, the Office of Naval Research (ONR) initiated the first phase of an Innovative Naval Prototype (INP) program that quadrupled the muzzle energy compared to previous guns, extended railgun barrel life from tens of shots to hundreds of shots, demonstrated full-scale launcher prototypes, developed reliable pulsed power technology with greater energy density; and began the task of projectile component risk reduction.

The electromagnetic railgun, after years of testing at land-based facilities, will go to sea for testing in 2016.

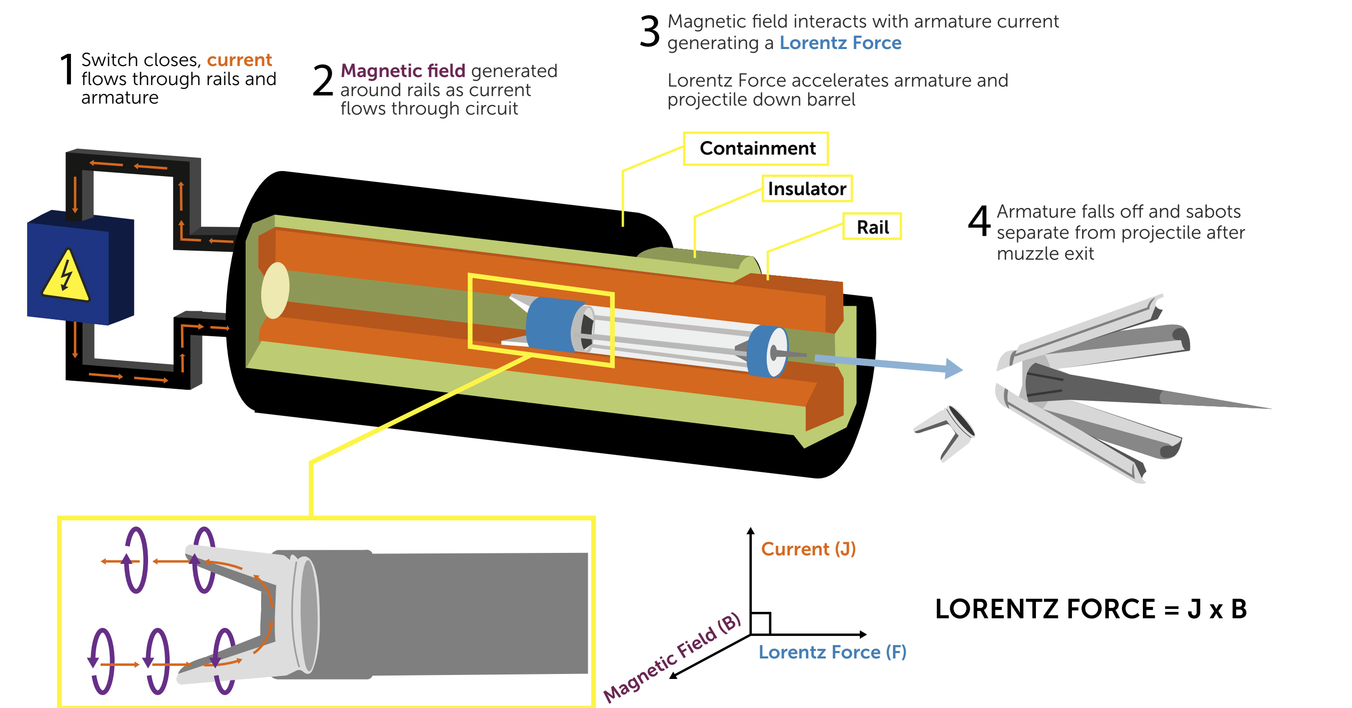
The maturation of railgun technology that accompanied these successes was matched by a growth in the mission set for a railgun weapon system. In addition to providing naval surface fire support, the potential railgun mission set now includes antiair and antisurface warfare—making the railgun a revolutionary, cost-effective, multimission weapon system.

In pursuit of the multimission capability, the second phase of the ONR railgun development effort began in 2012 to demonstrate an increase in barrel life while operating at a tactical firing rate. The shift from the first phase's manual-load operations to a firing rate of several rounds per minute is a significant step toward a deployable system. This next phase requires developing an autoloader and thermally managed barrel; a pulsed power system with active cooling and

Photo by John F. Williams

improved energy density, and modular packaging; and battery energy storage with active cooling. A truly national team with the top-notch personnel has been assembled to accomplish these goals: Navy labs (Naval Surface Warfare Center Dahlgren and Carderock Divisions and the Naval Research Laboratory); Department of Energy labs (Sandia and Lawrence Livermore); Johns Hopkins Applied Physics Laboratory; major contractors (BAE, General Atomics, Raytheon, L3); multiple small businesses; academia; and a significant number of interns.

FIGURE 1: HOW A RAILGUN WORKS



While the ONR Railgun INP focuses on barrel life and pulsed power development, three complementary railgun-related programs, building on the success of and working in concert with the INP, have contributed additional resources to develop the weapon system's other components. The ONR Hypervelocity Projectile program is developing a modular, precision-guided projectile (kinetic energy warhead) for use in the railgun that is compatible with the Navy's 5-inch guns (high-explosive or kinetic-energy warhead). The projectile effort includes developing an aerodynamic flight body with thermal protection, a kinetic-energy-based warhead, and guidance electronics packaged to fit within internal space limits and to survive high-g launch accelerations. The Office of the Secretary of Defense's land-based railgun experiment has initiated the development and integration of a fire control system and a gun mount. The Navy's sea base program is contributing to the mount design and will provide an at-sea demonstration in 2016, followed by a second enhanced demo by 2019. The wide flight deck and large cargo bay of a joint high-speed vessel will support the 2016 demonstration with only minor ship modifications. These four programs work within a single integrated master schedule and in an organizational structure that leverages the common elements to reduce risk and engineering costs.

A railgun capable of multiple missions will provide long-range fire support for warfighters ashore and protect surface fleet assets from various air and surface threats. Railgun hypervelocity projectiles offer distinct logistical advantages over propellant-based gun projectiles, including the reduction of explosives-related hazards. The ONR Railgun INP and Hypervelocity Projectile programs, in cooperation with the land-based railgun experiment and the Navy's sea base program, have made significant progress toward realizing the chief of naval operations' vision of the surface Navy's future weapon system.

About the author:

Roger Ellis is a program manager in the Office of Naval Research's Air Warfare and Naval Weapons Applications division. He has been involved in naval railgun technology development since 2000 as both technical director and program manager.

FUTURE WATCH

By Gil Graff

Tern is a joint Defense Advanced Research Projects Agency (DARPA) and Office of Naval Research (ONR) program to develop and demonstrate unmanned air vehicle technologies capable of small-deck takeoff and landing, autonomy, and sustained operations at very long distances from their host ships. The program is named after the family of sea birds noteworthy for their ability to fly for long periods while migrating thousands of miles.

The program, initiated in 2014 and expected to be complete in 2018, aims to provide situational awareness at distances well beyond the ranges achievable with current ship-based sensors and radars. In many situations, destroyers (DDGs) and littoral combat ships (LCSs) must operate without support from land- or carrier-based aircraft. Today, small-deck aviation resources, such as those aboard DDGs and LCSs, are limited to rotary-wing and very small fixed-wing aircraft. Helicopters, while capable of launch and recovery from these platforms, have limited endurance and a much smaller mission radius when compared with carrier-based, fixed-wing aircraft. With a rotary-wing sustainable mission radius of less than 200 nautical miles, significant portions of the global land mass currently are inaccessible by air vehicles employed from small-deck platforms.

The Tern program will develop and demonstrate technologies for a new class of medium-sized aircraft that would provide significantly enhanced Navy intelligence, surveillance, and reconnaissance (ISR) capabilities by using a fixed-wing, long-range/endurance solution that would operate from DDG- and LCS-class ships. For ISR missions, the program goal is to enable a persistent orbit at 600 nautical miles with 500 pounds or more of payload. The objective system must be capable of executing autonomous launch and recovery with minimal manpower and be compatible with small-deck aviation flight operations. Compatibility requirements include the ability to transit between the hangar and flight deck, to store and maintain the air vehicle, and to store spares and support equipment.

Tern builds on the Navy's past technology investments in automated launch and recovery and autonomous flight control, and on DARPA's work in air vehicle configuration advancements. The program will push beyond the limits of the vertical takeoff and landing (VTOL) aircraft that operate from today's ships. Current VTOL aircraft are inefficient cruise vehicles and consequently have limited flight endurance. Long-endurance and long-range fixed-wing aircraft have been demonstrated but require long runways for takeoff and landing. The challenge is to incorporate, in a single configuration, efficient flight, as well as shipboard VTOL. Previous studies have shown that the path to achieving both objectives is a vehicle that includes large wings for endurance, a large propeller swept area, and a propulsion system that provides control authority when operating around the ship deck.

To fit within ship hangars, the vehicle must have a very short fuselage with significant folding ability. Unlike helicopters, which use rotor-based controls, and conventional airplanes, which use relatively small propellers, the Tern vehicle wing-and-vertical-based controls must operate in the complex air flows in the large rotor wake. The transitions between launch and cruise flight and between cruise and recovery require control at large angles of attack. The large angle of attack aerodynamics is similarly difficult to predict. The complex aerodynamics unique to Tern vehicles result in major design, simulation and test challenges. Precision landing with near-zero roll in heavy sea states is particularly challenging on small deck ships, which can have significant pitch, roll, yaw, and heave motions. Onboard power must provide high-thrust operation for takeoff or landing and very efficient low-throttle operation for long endurance at cruising speeds.

The complexity of aerodynamics and the wind-over-deck environment are not easily replicated in subscale laboratory experiments. Full-scale flight testing at sea, therefore, is required to demonstrate risk reduction. In 2018, the Tern program will culminate in launch, recovery, and flight testing of a full-scale demonstrator vehicle consistent with a tactical vehicle in size, mass, aerodynamics, propulsion, and autonomous controls. Although not a production prototype, the Tern vehicle will demonstrate the characteristics required to evaluate future applications of this new class of aircraft as an innovative solution to current and future Navy ISR mission requirements.

About the author:

Gil Graff is a program officer with the Office of Naval Research and deputy program manager of Tern.

Tern

HOPING TO COMBINE UNMANNED AIR VEHICLE DEPLOYABILITY FROM SMALL DECKS WITH LONG ENDURANCE, TERN LOOKS TO MIMIC ITS NAMESAKE AS A "SEA BIRD" OF THE FUTURE.

Photo by Tom Grey

A LOOK AHEAD
USER'S GUIDE TO THE NRE

The next issue of *Future Force* will showcase articles on the various components of the Naval Research Enterprise (NRE), the overarching concept that joins together thousands of scientists, researchers, engineers, managers, and others involved in the planning, management, and implementation of science and technology research for the Navy and Marine Corps. *Future Force* brings you stories about specific projects from the NRE in every issue; in the spring issue, we'll showcase who comprises the NRE, what organizations participate in it, and how they go about making it all work.

The Office of Naval Research-sponsored Shipboard Autonomous Firefighting Robot (SAFFIR) undergoes testing aboard the Naval Research Laboratory's ex-USS *Shadwell* located in Mobile, Alabama. SAFFIR is a bipedal humanoid robot being developed by Virginia Tech to assist Sailors with inspection and damage control operations. Photo by John F. Williams.

R/V *Sally Ride*

Dr. Tam O'Shaughnessy, ship's sponsor for the research vessel (R/V) *Sally Ride* (AGOR 28), breaks a bottle across the bow during a christening ceremony at Dakota Creek Industries, Inc., shipyard in Anacortes, Washington, on 9 August 2014. After it is commissioned, *Sally Ride* will be sponsored by the Office of Naval Research and operated by the Scripps Institution of Oceanography at the University of California, San Diego, for the benefit of civilian scientists, exemplifying the many partnerships that go into the making of the Naval Research Enterprise.

Photo by John F. Williams.

A ballistic missile target is launched from the Pacific Missile Range Facility northwest towards a broad ocean area of the Pacific Ocean. Following target launch, USS *Lake Erie* (CG 70) detected and tracked the missile with its onboard AN/SPY-1 radar, developed a fire control solution, and launched an SM-3 Block IB guided missile to engage the target. Photo by MC2 Mathew J. Diendorf.

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