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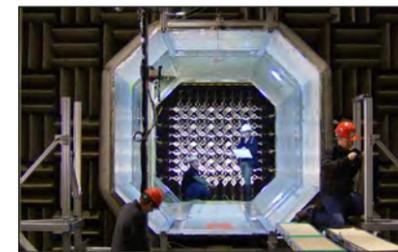
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**Future Force** is a professional magazine of the naval science and technology community. Published quarterly by the Office of Naval Research, its purpose is to inform readers about basic and applied research and advanced technology development efforts funded by the Department of the Navy. The mission of this publication is to enhance awareness of the decisive naval capabilities that are being discovered, developed, and demonstrated by scientists and engineers for the Navy, Marine Corps, and nation.

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Our Navy and Marine Corps are in a high stakes competition for maritime superiority. The competition is to be the first to field decisive capabilities. While accelerating technologies through product development and acquisition will gain a near-term edge, we must never forget that new knowledge is the real source of future competitive advantage.

Solutions to naval and national challenges begin in the lab. Often behind the scenes, basic research conducted by naval scientists or supported universities provides the seed corn of future breakthroughs. This doesn't happen overnight. Hard-won new knowledge is the foundation of innovation. Sustaining research vital to the sea services is the purpose of basic research—and this must continue.

The Office of Naval Research (ONR) is uniquely qualified to select and fund basic research targeting future force attributes to be (according to the Future Fleet Design Group): faster, adaptive, autonomous, defensible, lethal, scalable, and efficient. Such enduring research efforts consist of broad-based scientific work—discovering new materials, better understanding the naval operational environment (from sea floor to space), and leveraging our understanding of the human brain's inner workings.

Much of this work is conducted at the Naval Research Laboratory, the nation's first federally funded lab, established in 1923. More broadly, coordinated activities across ONR's network of partners leverage thousands of world-class researchers across academia, industry, and other government labs. High-priority topics that intersect more than one traditional technical discipline serve to stimulate innovations, accelerate research progress, and expedite transition of results into naval applications.

Enduring research is a prudent and essential long-term hedge against an increasingly uncertain and dynamic security environment. For more than 70 years, ONR has overseen research in critical areas requiring a distinctive naval science and technology base ensuring that US naval forces project power effectively.

This issue of *Future Force* highlights examples of research and discoveries supporting our Sailors and Marines today. As you will see, we don't lack good ideas or talented people. The challenge we face today is matching the rate of technology deployment with the accelerating pace of development. By working with the best and brightest, ONR will continue to evolve how we meet our innovation mission in a more interconnected and interdependent world.

**Rear Adm. Hahn is the chief of naval research.**

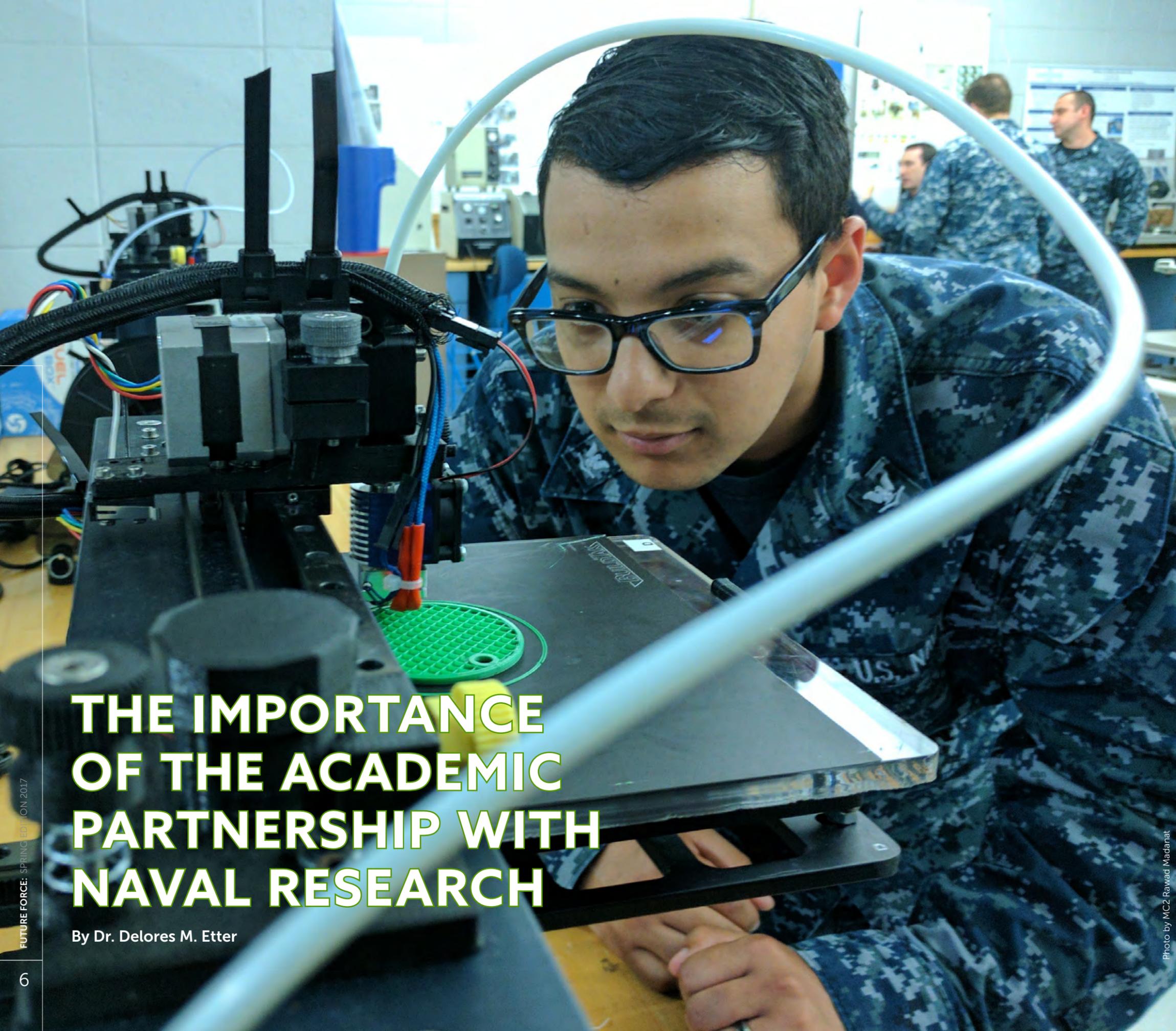
Photo by MC1 Elliott Fabrizio



Chief of Naval Operations Adm. John Richardson visits with leaders at the Naval Research Laboratory to review their work developing new technologies and scientific research initiatives.

## Basic Research

Enduring research helps sustain knowledge discovery that is unique to the naval services. Nominally identified under the Department of Defense Financial Management Regulation as 6.1, basic research is defined as systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and/or observable facts without specific applications toward processes or products in mind. Basic research has the widest possible application across civilian and military endeavors, but it is also the essential prerequisite for any and all technology that eventually makes it into the fleet.



# THE IMPORTANCE OF THE ACADEMIC PARTNERSHIP WITH NAVAL RESEARCH

By Dr. Delores M. Etter

**THE NAVAL SERVICES' TIES WITH ACADEMIA RUN DEEP—THIS INFORMATION SYSTEMS TECHNICIAN IS LEARNING 3D PRINTING AT OLD DOMINION UNIVERSITY—AND ARE MUTUALLY BENEFICIAL.**

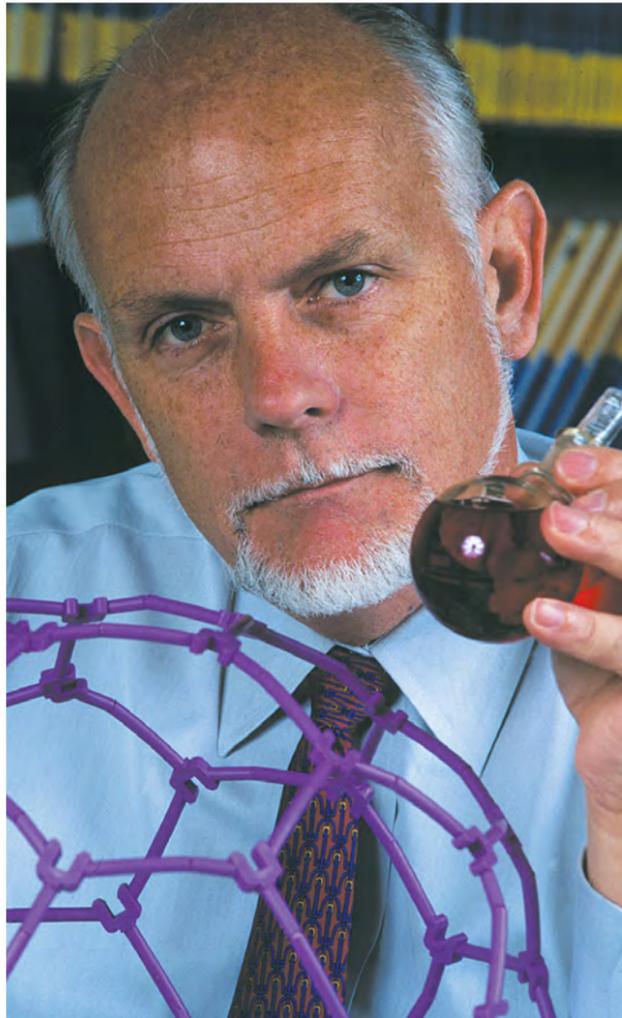
**T**he importance of the partnership between academia and naval research is often underestimated. This partnership is a win-win opportunity, but the benefits are especially significant to the Navy and the Marine Corps. This article discusses these benefits in the context of access and impact. It also discusses some of the issues that often arise in discussions regarding academic research, including classified research, entitlement, time cycles, research focus, and cost-effectiveness.

## Background

In this article, I will offer perspectives from within the academic community, and also from within the naval research community; therefore, I think a brief summary of my experiences is important to establish credibility within both communities.

My career has taken me on a path not typically followed by academics. After completing my doctorate, I accepted a faculty position in the electrical/computer engineering department at the University of New Mexico. My research area is digital signal processing and I had research connections with Sandia Laboratories that began with my dissertation research. These collaborations also led to classified research that involved obtaining security clearances. During the first 10 years of my career, I focused on academics (teaching, research, and professional activities); I spent a year as a visiting professor at Stanford and then moved to the University of Colorado. Around this time, I was also invited to participate in an Air Force studies board committee to review the Air Force's tactical communication systems in Europe and the United Kingdom. This interaction required a security clearance and drew on my signal processing background. This committee interaction was the beginning of a 25-year collaboration with the Department of Defense (DoD) and the intelligence community. I became more involved with DoD advisory committees, I chaired the Naval Research Advisory Committee, and was a member of the Defense Science Board for a number of years. These committees gave me access to internal discussions

Photo by MC2 Rawed Madanat



Former ONR principal investigator Richard Smalley received the 1996 Nobel Prize in Chemistry for the discovery of a structure of carbon atoms known as “buckyballs.” (Photo courtesy of Brookhaven National Laboratory)

within the leadership of the Navy and the DoD, and I led a number of technical studies on topics related to national security. In 1998, I had an opportunity to spend three years in the Office of the Secretary of Defense as the deputy under secretary of defense for science and technology. In this role, I had oversight responsibility for the Department of Defense’s science and technology programs, and I was the US representative to the NATO Research and Technology Board. In 2001, I accepted a faculty position at the US Naval Academy in the electrical engineering department, and developed a research laboratory in biometrics research that was funded primarily by the intelligence community. In 2005, I was confirmed as assistant secretary of the Navy for research,

development and acquisition, and served in that position for two years. Much of my time in that position dealt with acquisition issues, but I also spent as much time as possible interacting with the Navy and Marine Corps research laboratories, system commands, and warfare centers. In 2008, I returned to academia as an endowed chair at Southern Methodist University, and continued my research program in biometrics; I retired as professor emeritus at the end of 2016.

### The Importance of Access to the Academic Community

The importance of access to the academic community by the naval research community is evident in a number of areas, but I think it is especially important in three areas.

**Early Access to Research:** Universities are the home of state-of-the-art research in many areas of special interest to the Department of the Navy. These areas include communications, computing, oceanography, materials research, cognitive research, and power sources—this is just a sampling of the areas important to the Navy and Marine Corps. Partnerships with the faculty and the academic institutes and centers in these areas provide early access to these results, whereas waiting for publication of research results delays the ability of the naval research community to assess results that might have special significance.

**Early Access to People:** Partnerships with universities also provide opens doors to people, both faculty and students. Having personal connections is as important as the access to the latest research. Involving faculty and students in naval research through sabbaticals, summer research programs in naval facilities, and student internships is a way to begin relationships that can last for entire careers. It is particularly important to build relationships with students, both graduate and undergraduate. These students are future collaborators from academia and industry, and they also are ideal candidates to recruit for positions within the naval research community. I will add here that I am especially pleased to see some progress in the ability of the Navy to make more competitive and timely job offers than in the past. This is an area that still needs improvement for the department to be as competitive as it needs to be for the top talent.

**Areas of Naval Interest:** The ability to share naval research areas of interest and priorities with faculty is especially

important. Many faculty members (and even the general population) today do not have much direct involvement with the national security community. If faculty members understand the potential connection of their research to areas of national security, they often find it more interesting or more compelling to focus on those areas.

### The Impact of Naval Funding on Academic Research

Note that this is the first time I have mentioned funding to universities. The areas of access that I have already mentioned help develop relationships and involve faculty and students in naval facilities, but none of them involve the Navy having to spend money to make them happen.

Direct funding to academic researchers is clearly the quickest way to develop partnerships, and the Navy has always done this better than the other services.

The Office of Naval Research (ONR) and the Naval Research Laboratory (NRL) provide the largest amount

of naval funding of academic researchers, but significant funding also comes from program executive officers and other naval organizations. This funding has allowed direct access to researchers in areas critical to naval technology developments.

The significance of this funding can be seen in a number of ways. For example, the list of the Nobel Prize winners (or winners of other national and international research awards) includes many who have been funded by the Department of the Navy. If you consider the important capabilities of our warfighters today, you can trace aspects of these capabilities back to academic researchers. Here are three examples of university researchers who have been critical partners to naval research: Walter Monk from Scripps Institution of Oceanography in the University of California, San Diego, and his work in ocean circulation and its role in Earth dynamics; Andre Geim and Konstantin Novoselov, both of the University of Manchester, for their discovery of a new material called graphene; and Richard Smalley from Rice University and his discovery of buckey balls, which has



ONR principal investigators Andre Geim (right) and Konstantin Novoselov (left) received the 2010 Nobel Prize in Physics for their discovery of graphene. (Photo by AP)

created a new area in chemistry.

Direct funding to academic researchers is the quickest way to increase work in areas of specific interest to the Navy, and it is the quickest way to help focus a faculty member's research into areas of specific interest to the Navy. Funding to academic researchers is often basic research (6.1) but there also are many partnerships in developmental research and applications (6.2 and 6.3). As an aside, a university researcher always remembers a few things—the first conference where you presented a research paper, the first refereed journal article that gets accepted, and the first external research grant. (In my case, it was the IEEE Asilomar Conference, the IEEE Transactions on Acoustics, Speech, and Signal Processing, and an ONR grant. The fact that I even remember what dress I was wearing when I presented the conference paper says something about how much it meant to me.)

### Issues Related to Academic/Naval Partnerships

Here I will address some of the issues I think are important to mention relative to academic research partnerships, particularly those that involve direct funding.

**Classified Research:** Some large universities have very sophisticated organizations to work on classified research programs. Most universities, however, do not have on-campus facilities to work on classified research. Most academic faculty, staff, and students also are not trained in the required care that is needed to work with classified research. As a result, a naval organization that wants to do classified research with academic researchers needs to be very careful with these arrangements. There are a number of successful situations in which the academic research team can use classified facilities at local defense manufacturers. Of course, this all assumes that the academic researchers have clearances—that also can be another roadblock to classified research.

An important tenant of academic research is expanding knowledge; this new knowledge often is part of the research program for graduate students. In these cases, this newly acquired knowledge is typically part of thesis and dissertation research that is unclassified and included in research publications that are available globally. My experiences lead me to believe that a great deal of important research can be done without being classified as long as it is done in theoretical situations or in very

general applications. I think classification issues can generally be dealt with in ways that still allow academics to participate in or to contribute to research that has classified components.

**"Entitled" Professors:** Over the years, I have heard a number of people in the naval community express concern over professors who feel they are "entitled" to naval research funding. Most of the time, the people who express this concern are in the military, and do not have direct contact with academic research. In my experience of more than 25 years observing research interactions between academic and naval organizations, I have never seen a blatant case of such entitlement. That doesn't mean it doesn't exist, but I have to believe that it is a very small number of professors that have a sense of entitlement to naval research funding. It is possible some of these concerns actually are more related to my next topic.

**Time Cycles:** When I accepted a graduate student into my research program, it was almost always with the offer of a research assistantship that included a monthly stipend and tuition. For most of these students, they were only able to attend graduate school as long as they had a research assistantship. Generally, funds for research assistantships come from research grants, so without research grants, it can be very difficult to find outstanding research students. Furthermore, it is very disruptive to a research program to run out of funding in the middle of a graduate student's thesis or dissertation research. As a result, faculty try very hard to match a graduate student's research program to the length of a research grant. Hence, research grants of one year are very difficult to match to a graduate student. Research grants of two to four years work much better in terms of matching outstanding graduate students to a research effort that has time to do the necessary background investigations, modeling, theory/algorithm development, experimentation, and evaluations that are necessary for significant research results. I suspect it is this effort to set up multiyear research programs with naval organizations that is sometimes viewed as unreasonable or "entitled" expectations. I want to be very clear here, however, that I am not in favor of research programs without accountability. Every funded research program should expect regular research updates, reviews, and feedback. The research needs to address the goals and direction agreed upon in the research agreement, and if progress is not being made, it is very reasonable to consider closing down the research project under the conditions of the contract.



Walter Munk first received support from the Navy for his research on wave action and oceanography beginning in 1946. Still working more than 70 years later (at the age of 99 years young), he is the Navy's longest continuously supported principal investigator. (Photo courtesy of San Diego Union Tribune)

**Research Focus:** The development of new knowledge is one of the most important goals in basic research. When a research program is extending our current knowledge, it is possible to predict, or model, what direction the research will take, but it is the unexpected results that are the most significant, and the most disruptive. The more one tries to narrow, or focus, the direction of a research program, the less likely one is to get these unexpected results. And in the end, from a naval perspective, we are really trying to develop new capabilities that can be used to support national security. Thus, research projects with very specific deliverables and directions are probably better candidates for industry and consultants.

**Cost Effectiveness:** The last topic I want to mention is the cost effectiveness of adding research staff to a research project, especially undergraduate students. I want to encourage each of you that funds university research projects to consider adding a few extra dollars to new contracts that you fund, or to add a few dollars to currently existing projects that you already fund, so that the principal investigator can hire undergraduate students during the summers and during the academic year. Many of my best graduate students started working with me as undergraduates, and I was able to encourage

them to continue to graduate school because they had gotten involved in some very interesting research. We all know how important it is to get more university graduates in STEM (science, technology, engineering, and mathematics) areas, and hiring undergraduates in research programs is inexpensive and very effective.

### Conclusion

I appreciate the opportunity to share my perspectives on the importance of the partnership of academia and the Department of the Navy's research programs. Our national security future depends on continuing to provide state-of-the-art capabilities, and disruptive capabilities, to our warfighters—and this requires a long-term commitment to outstanding researchers in academia, in industry, and in the naval research laboratories. ✈

### About the author:

**The Honorable Delores Etter** is professor emeritus at the Southern Methodist University School of Engineering, and former assistant secretary of the Navy for research, development and acquisition.



Chief of Naval Operations Adm. John Richardson visits Carnegie Mellon University in Pittsburgh to discuss learning sciences and artificial intelligence research.

# WHY EVERY RESEARCH PORTFOLIO SHOULD INCLUDE BASIC SCIENCE

By Lt. Adam T. Biggs, USN, and Lt. Todd R. Seech, USN

**THE SIDE PREPARED TO FIGHT IS THE SIDE THAT WINS THE BATTLE—AND BASIC SCIENCE RESEARCH PROVIDES THE FIRST STEP IN BEING PREPARED.**

Like all aspects of the military, the research and development sector thrives on a foundation of cause and effect. Applied research questions more easily match this formula because you can make concrete claims such as “this widget increases accuracy by 32 percent,” or “new training protocols have reduced Class A flight mishaps by 18 percent.” Basic science has a more indirect connection to operational outcomes, which often makes its utility easier to overlook. This oversight, however, creates a critical vulnerability in the military research and development structure that can leave operational units performing below their maximal potential.

Consider one fundamental need of military readiness: The tactics of tomorrow will be different than the tactics of today. Although this statement may have been accepted as a truism in military communities for centuries,

it is not always clear how to take tangible steps toward tomorrow. Although applied science research helps to address this issue, basic science research allows us to explore tomorrow’s tactics today—making basic research an investment into our future readiness. The battlefields of tomorrow are being built as we speak, and pieces on the board can be set into motion decades in advance.

Our future capabilities will be built on projects that advance basic science. Still, there are numerous challenges between then and now that must be met and overcome. For example, how do you justify basic science expenditures amidst the flurry of immediate needs our forces face today? What kind of basic science should the military pursue? How do you evaluate the potential of a basic science project? These are the types of questions we will address here.

## A 6.0 Problem in a 6.1-to-6.7 World

The Department of Defense and academia differ in how research is described. These differences can lead to confusion about different projects or research announcements, which is why it is important to understand a critical distinction in research language. Academics often use a simple division of basic or applied science. Basic science is the pursuit of knowledge to advance (or overturn) current theoretical consensus, whereas applied science is the application of basic science knowledge to a concrete problem. Defense research uses the 6.1 to 6.7 scale: science and technology activities are 6.1 to 6.3 efforts, whereas test and evaluation activities are 6.4 to 6.7 efforts.

The problem is that academic basic science—and what most people consider basic science—is not really even 6.1. This type of research is what could be called a “6.0” effort. In this sense, 6.0 describes basic science research that the National Science Foundation (NSF) would fund. Some scientists may submit to an Office of Naval Research (ONR) call for basic research with a project that does not fit because they confused 6.0 research for 6.1 research. The confusion can waste time during review, or, worse, limit the scope to which academics and other scientists seek to engage ONR collaborators. Of course, 6.0 is not actually a defense research label, but rather something used here for illustrative purposes to describe how confusion can arise between academic scientists and military scientists—especially when everything from 6.1 to 6.7 research gets lumped together as “applied.”

The difference between 6.0 and 6.1 is simply establishing that link of military relevance. Academic researchers call this distinction basic versus applied science. Many 6.0 university scientists are still doing great things to further our understanding of the universe, and military researchers can appreciate their efforts and findings. Ultimately though, the military research continuum begins at 6.1 because military research and development, even basic science research, is conducted with some more specific goals in mind.

Perhaps an ideal example of 6.0 research involves certain zoology projects. For example, biologists may study the mating habits of certain tree beetles before and after deforestation. This idea and pursuits like it are intended to create a better understanding of the world around us. The military application is not always obvious in these basic science pursuits. The catch is that if a military purpose becomes clear, it often becomes very, very clear. How atoms form bonds is a basic science question—the power of splitting an atom is a military advantage capable of ending wars.

This 6.0 problem helps highlight the first hurdle to overcome in understanding why the military should pursue basic science. Specifically, why should the military be interested in answering a 6.0 question? The answer is simple: We should not. The mating habits of tree beetles may alter our understanding of the world around us, and these studies are certainly worthy of further investigation. But other organizations—such as NSF—exist to answer questions and advance knowledge. NSF projects may change our view of the universe or develop new technology and products that revolutionize our economy. Military research organizations have a more concrete mission that directly builds on preparing our personnel for battles today and tomorrow.

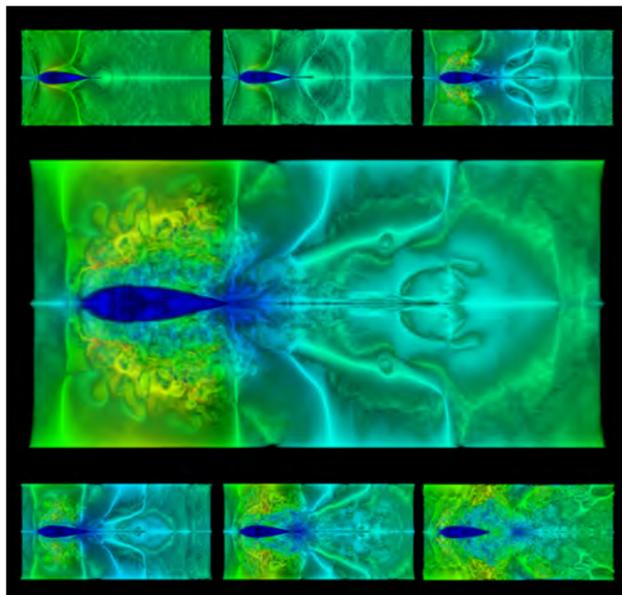
## Why We Need Basic Science

Definitions aside, basic science research can still have direct effects on Navy and Marine Corps policy and procedures. Basic science is how we understand the problem, and understanding the problem is a key step in finding a solution. For example, a well-known problem in military aviation is called the “Black Hole Illusion.” Aviators sometimes have to land on military air strips when there is no moon and/or minimal peripheral illumination. The illusory effect causes aviators to adopt a glide path that is too shallow, which if not recognized soon enough may cause them to crash short of the runway. We know that the Black Hole Illusion is a problem; what we do not know is what causes the illusion. What perceptual processes become altered or deceived that cause aviators to misjudge the runway and their glide slope? The Naval Medical Research Unit Dayton specializes in aerospace and medical research, and we are currently examining the issue through an ONR In-house Laboratory Independent Research project. Our basic science experiments involve perceptions of line orientations under various experimental conditions. On the surface, these experiments are basic science investigations into how humans make perceptual judgments about the slope of lines. There is no obvious military purpose—until you consider that this information could help inform new training procedures or even runway design to help aviators avoid the Black Hole Illusion and Class A mishaps (i.e., involving significant property damage or a fatality).

We need basic science because a better understanding of the problem leads to better solutions. There are many examples in addition to the aviation issues described already, but these examples all demonstrate how basic science could apply to the military. The true challenge is in quantifying the results. Cause and effect are integral

to military evaluations, and applied science fits this mold more directly. Basic science efforts do not always provide clear-cut advantages in the days, weeks, or years that follow the project. For example, directed energy weapons first required substantial basic science research. Einstein laid the theoretical foundations for lasers in his paper “On the Quantum Theory of Radiation” in 1917. Our Navy did not field test a laser weapon system on USS *Ponce* (AFSB[I] 15) until 2014. Nearly 100 years of basic science advances were necessary to take Einstein’s ideas, test them, replicate the results, transition those findings to useful products, and finally create a field-ready laser system capable of military applications. Under normal circumstances, however, no project sponsor is going to be receptive to a science-to-application window of a few decades longer than the average human lifespan.

So how do we quantify basic science research in such a way that it can be appreciated in a much shorter time frame? After all, everyone involved in the research chain—from the research assistants to the project sponsors—have someone else to whom they must quantify the project results for yearly evaluations. This quantification is easy in academia if you consider project success in terms of conference presentations, papers published, and the journal impact factors of where those papers were



It can sometimes be fine line between a “6.0” and a 6.1 project—this research looking at water flow turbulence at the University of Texas at Austin and the Lawrence Berkeley National Laboratory was supported by the National Science Foundation, but it has direct relevance for naval engineers as well. (Photo courtesy of National Science Foundation)

published. Unfortunately, these metrics do not translate to military operations, where tangible improvements to naval operations are the coin of the realm. There is, however, a way to bridge the gap between these different currencies.

### Making Basic Science Relevant

There is a way to make basic science more relevant to naval operations and provide appreciable metrics for military evaluation. The simple solution is to incorporate more operationally-relevant variables into studies. ONR is perhaps the world leader in supporting this particular idea, where 6.1 basic science is conducted with operational outcomes in mind. An operationally relevant variable, such as shooting accuracy, can help link even a basic science investigation to an operational environment. We gain a better understanding of the problem while also keeping our scientific initiatives firmly grounded in scenarios that will help naval operations.

This approach is often easier said than done, and direct relationships between science and operations are not always possible, but there are opportunities to enhance existing studies. For example, one study compared Transportation Security Administration (TSA) officers against university undergraduates on a visual search task. The goal was to understand and identify behavioral differences in how people conduct a visual search for targets. The experiment used a simple paradigm where both TSA officers and undergraduates could identify targets, which put the two groups on equal footing. Accuracy is then an operationally relevant variable for the Department of Homeland Security (DHS), the research sponsor, and this study allowed for basic science investigations into the mechanisms of visual search while remaining relevant and appreciable for DHS.

A similar step can be taken toward naval relevance in visual search. Searching the road for improvised explosive devices (IEDs) is another visual search process, and understanding the mechanisms of visual search could help improve procedures for clearing roads of IEDs. Accuracy and speed are variables that translate well into appreciable military terms—did you find all the IEDs, and how long did it take? Another approach is to make the stimuli match the operational environment as much as possible. Intermix the letter searches used by academic investigators with more actual roadside search scenes. This approach will not always work, especially if the scenario requires some form of expertise, but it provides



The Navy did not field test a laser weapon system on USS *Ponce* (AFSB[I] 15) until 2014. Nearly 100 years of basic science advances were necessary to take Albert Einstein’s ideas, test them, replicate the results, transition those findings to useful products, and finally create a field-ready laser system capable of military applications. (Photo by John F. Williams)

an example of a way to frame basic science in more operationally-relevant terms by using more operationally relevant metrics.

Although human performance initiatives can be linked fairly easily to an operational scenario, this idea can be more difficult to apply in basic science terms for other areas. For example, chemical research may investigate how molecules bond, which could help develop new polymers that extend the durability of certain plastics. This research could still be couched in operationally relevant terms if you can align the scope of the overall problem with a military issue. Perhaps protective gear needs to be lighter or more disposable, and these new polymers will help reduce costs or extend product usability. Somewhere along the way though, there needs to be a connection between the basic science initiative and the eventual applied end goal. Identifying these links is essential; even if the product, procedure, or other outcome will be years in the making, the potential must be clear today. If not, we have fallen off the military spectrum and back into 6.0 research.

### Summary

Basic science is essential for military research and development. Advances in this area are how we prepare

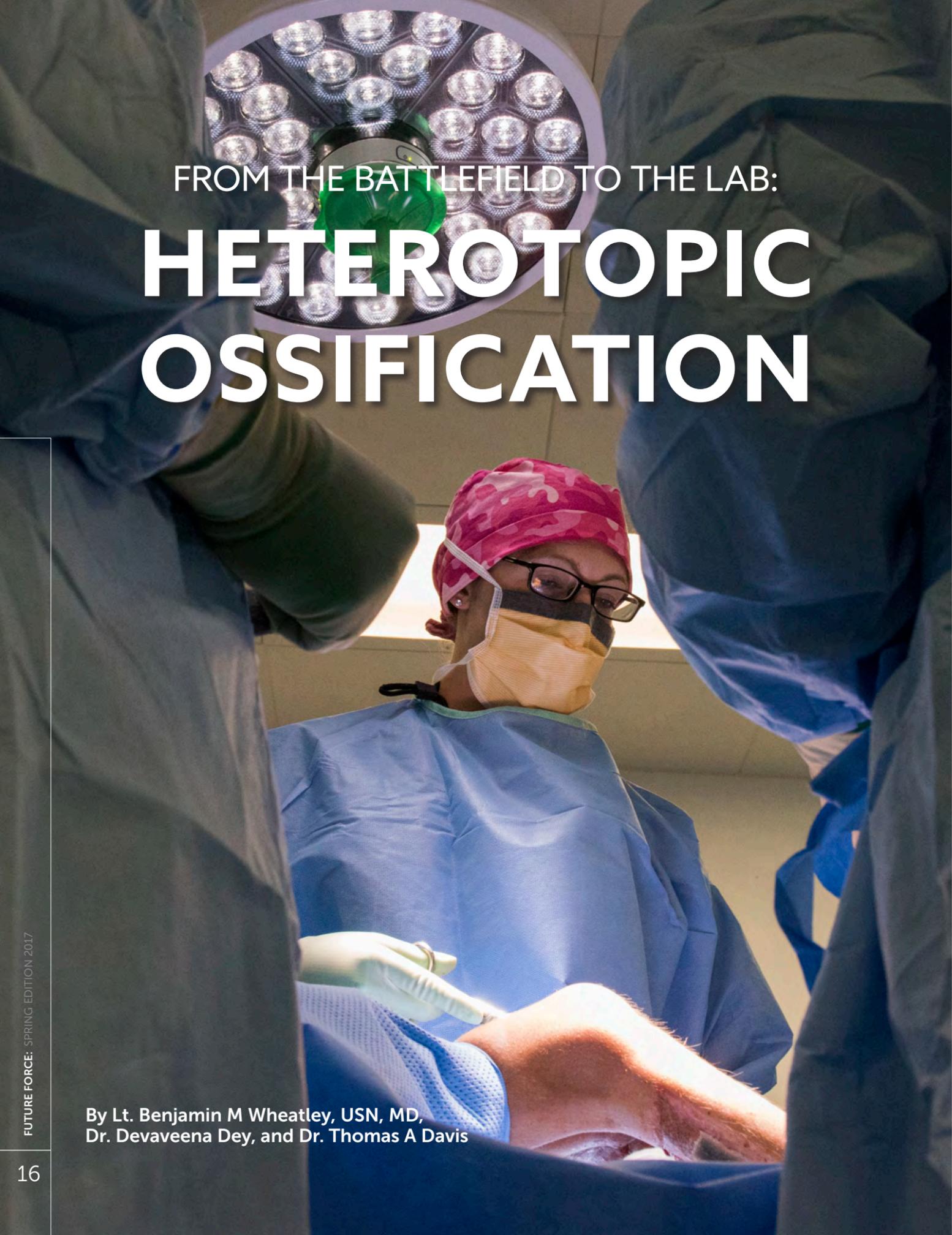
for future battlefields that exist closer to science fiction than current science fact. Still, not all basic science should be pursued by the military. Some science endeavors remain too academic to justify a military investment. This grouping represents the “6.0” research conducted at some universities, whereas military basic science always has some relevance for current or future operations. Even if that relevance is rooted in potential more than practicality, the connection should be clear.

These ideas provide a few important things to consider. First, the military must pursue basic science. Any portfolio without some basic science research is not looking sufficiently far enough down the road. You may understand the problem today, but true leaps forward will require broader thinking, which needs a better understanding of the problem. Second, not all basic science falls within the military purview. These initiatives, while insightful and groundbreaking in their own right, can be funded by other sources. The military should pursue basic science with some potential to eventually transition into more applied research. Third, the greatest challenge to military basic science is quantifying the contribution of basic science experiments. The easiest approach is to use dependent variables that more closely align with the military mission. When these operationally relevant variables are not applicable, then the science-to-operations link must be clear. Impact can be measured in many different ways, and even if the potential will not exist for many years, justification will depend on that link and its corresponding possibilities.

Ultimately, basic science and applied science are not two opposing forces or two competing entities. They are two pedals on a bicycle, each propelling the other forward. Understanding the problem will help you find solutions, and the search for solutions can further yield insight into the problem. Operational challenges need basic science and applied science initiatives because they both help you solve the problem. Each approach is merely a different way to tackle the larger issue. One time-tested maneuver is to flank a hostile force—attack them on multiple fronts. It only makes sense for military science to make good use of an established military tactic. ✈

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FROM THE BATTLEFIELD TO THE LAB:

# HETEROTOPIC OSSIFICATION

By Lt. Benjamin M Wheatley, USN, MD,  
Dr. Devaveena Dey, and Dr. Thomas A Davis

TRAUMATIC AMPUTATIONS HAVE LONG BEEN A TERRIBLE SCOURGE OF THOSE INJURED IN WAR, AS HAS THE LESSER-KNOWN BUT PERSISTENT PROBLEM OF EXCESSIVE BONE GROWTH IN THE AFTERMATH OF AMPUTATIONS. THIS OLD CONDITION SUFFERED BY WOUNDED WARRIORS IS GETTING NEW ATTENTION AT THE NAVAL MEDICAL RESEARCH CENTER.

Advances in medicine and technology often followed times of great conflict and war. The modern ultrasound can trace its roots back to World War I when it was developed to track and sink German U-boats. That same war saw the development of plastic surgery because of a large number of war casualties with facial wounds requiring reconstruction. Synthetic rubber, blood banks, ambulances, improved antiseptics, and vaccinations were all developed during times of war.

In our research efforts at the Naval Medical Research Center, in collaboration with university partners, we have seen an old problem, heterotopic ossification (HO), come to the forefront at an unprecedented rate. Written descriptions of HO can be found in medical notations from World War I, and even as far back as the American Civil War, in which excessive bone growth could be found following traumatic amputations. Heterotopic ossification is the formation of bone where it is not supposed to be, such as in muscles or other soft tissues. This aberrant bone commonly forms following severe trauma including crush injuries, burns, and blast injuries. More recent conflicts in Iraq and Afghanistan have seen a relative increase in extremity injuries because of the advances in body armor and its association with blast injuries. Heterotopic ossification has plagued the wounded and the doctors who treat them over the past 16 years. In a pivotal clinical research study conducted at the Walter Reed National Military Medical Center, the *Journal of Bone and Joint Surgery* (Potter, 2013) reported as many as 65 percent of combat-injured service members who sustained an amputation went on to develop HO.

Heterotopic ossification, at times, can be severely debilitating and painful during the rehabilitative phase of a patient's care. Since bone is forming where it is not supposed to be, it can crowd or press against other structures such as nerves and muscles in their normal position. It can also create wound healing problems and difficulties with prosthesis fit and wear. If it forms near a joint it may lead to contractures or a decreased range of motion. All of these can make it difficult, if not impossible, for patients to regain their independence.

Prior to the current conflicts, HO was not a common problem in military medicine and it was not seen nearly as often in civilian trauma. The recent wars generated a great deal of interest in understanding the mechanisms behind HO development so we could develop effective treatments.

A two-pronged approach was developed by researchers at the Naval Medical Research Center in collaboration with doctors at Walter Reed National Military Medical Center and university researchers. This included clinical research studies of patients who developed HO and bench-level laboratory research developing a model to recreate the injury patterns commonly seen in combat. Initially, two injury patterns were identified that were commonly seen in the clinical experience.

The first was a blast overpressure model, which is the concussive force experienced in proximity to an explosion (such as an improvised explosive device). The second was a severe extremity injury model of a femur fracture followed by a prolonged crush injury and finally an amputation through the "zone of injury." The zone of injury refers to an area surrounding a wound that may appear normal at first but is actually damaged by the initial injury.

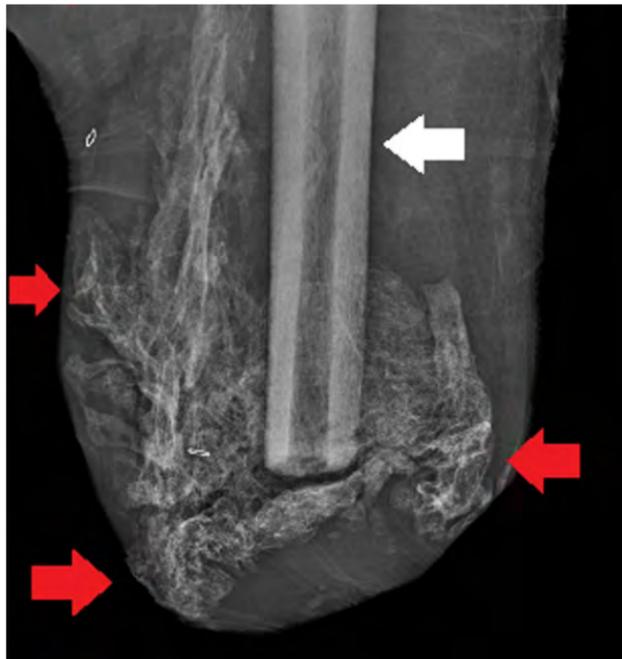
These two injury models were tested in isolation and in combination to determine their effect on the amount of HO formed. We found the combination injury led to a significantly greater amount of bone formation than either injury model alone, and it did so consistently. This gave us the model we would use to further characterize the pathways in HO on a molecular level.

Once the laboratory model was created, our next goal was to characterize the cell signaling pathways and gene expression that ultimately produces HO. Gene expression is the process by which various portions of DNA are turned on or off to produce, or stop the production of, various proteins. These proteins direct the function of a variety of cells, including those that form bone. Genes may be differentially expressed during times of growth, stress, or injury as the body compensates to the change in its environment to maintain homeostasis.

US Air Force photo by Tech Sgt. Tyrone Lawson

By microscopic analysis of the cellular composition, we know the bone formed by HO is normal bone in its appearance and cellular structure, closely resembling the long bones in the body such as the femur and tibia. What makes it abnormal is the location. Long bones in the body are typically formed by a process called “endochondral ossification,” when bone is formed by first laying down a cartilage scaffold that is slowly replaced by bone cells through a complex cellular mechanism. Interestingly, the bone formed during HO follows the same mechanism.

Following the injury, early cartilage cells could be found propagating in the injured tissues. Many of the genes involved in the production of inflammatory molecules, cartilage, and bone were expressed at levels that were orders of magnitude higher compared to the uninjured controls. The variable expression of these genes changed over time with some initially up-regulated and later down-regulated and vice versa. By understanding these early cellular and molecular changes occurring in HO, we can better understand the disease process and progression. This in turn will help us to develop therapies directed to specific cellular and molecular targets to interrupt the process early on.



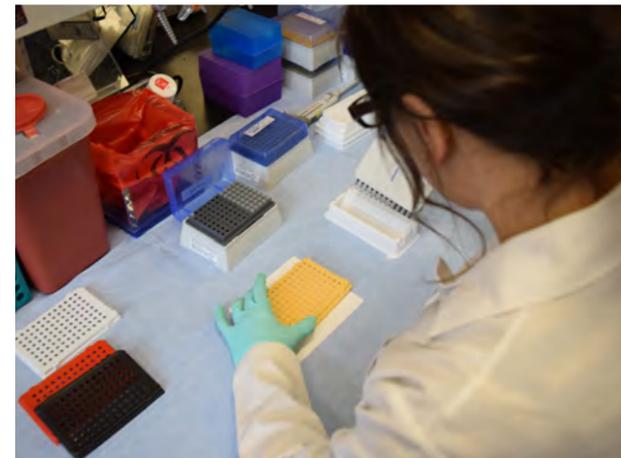
This figure shows an X-Ray of a femur three months after an explosion resulted in an above-knee amputation. There is extensive heterotopic ossification formation in the muscles surrounding the residual limb. The white arrow indicates the normal bone of the femur while the red arrows indicate the abnormal, heterotopic ossification that has formed.

Our laboratory model was still too simple at this point. The blast injuries service members sustain are complex, with open injuries highly contaminated with dirt and debris. These injuries require multiple surgeries to control infections and promote healing, all of which can increase the inflammation in the wound and promote the formation of HO. Our initial injury model was fine-tuned to more closely recreate a typical injury pattern by introducing a bacterial infection into the wound.

Returning to the clinical research, a study of the bacteria in wound infections found that nearly 25 percent involved a bacterium called methicillin-resistant *Staphylococcus aureus*, or MRSA. Our studies of the early characterization of HO, as well as other HO studies available in the literature, point to increased inflammation as a potential driving factor in the development of heterotopic bone. We hypothesized that by including a bacterium, which is commonly found in wound infections, we would increase the local inflammation and thereby facilitate HO development. We did, in fact, find the introduction of MRSA resulted in a significant increase in the amount of bone formed compared to those without bacterial infection. With the new laboratory model finalized and the early characterization of gene expression complete, we next focused on treatment.

In addition to blast injuries, HO also develops following some major surgeries such as hip and knee replacements. This type of HO has been studied extensively in the civilian population by universities and researchers across the country to improve outcomes following surgery. Two treatments have been developed in these patients to prevent the formation of HO following surgery. They are nonsteroidal anti-inflammatory drugs, such as Ibuprofen or Motrin, and local radiation therapy, similar to that used in cancer treatments but at lower doses. While these treatments are effective in a patient undergoing surgery, neither is practical in combat-injured service members returning from the battlefield to military treatment facilities in the United States.

Once HO is established in an injured extremity, it can only be treated with surgery in which the offending bone is removed. Surgery to remove HO can lead to set backs in healing and rehabilitation and carry the risk of recurrence. An ideal therapy would be easy to implement in an austere environment and selective to prevent unwanted side effects. To date, we have studied three different therapies in the laboratory model, each of which act on different parts of the disease process.



Naval Medical Research Center researcher Allison Tomasino prepares an experiment as part of a project being done on heterotopic ossification. (Photo by Naval Medical Research Center Public Affairs)

The first substance tested was Palovarotene. This drug was originally developed for the treatment of chronic obstructive pulmonary disease, but it was later found to block new bone formation. This led to its use in a rare, genetic form of HO called fibrodysplasia ossificans progressiva, or FOP. Both HO and FOP are similar in the formation of abnormal bone in soft tissues, but bone growth in FOP is triggered either spontaneously or after a relatively minor trauma, such as vaccination, where bone is formed at the site of injection. Palovarotene works by preventing the formation of the cartilage scaffold which later turns into bone. When applied to our laboratory model, we found this drug did lead to a significant reduction of HO as measured by the total volume of bone formed. As expected, the gene expression for cartilage and bone producing cells was also reduced. There was a trend, however, toward increased wound healing complications or delays in the laboratory model studies with Palovarotene.

The next drug tested was Rapamycin, which is typically used to prevent organ rejection after transplants. It has both immune suppressive and anti-inflammatory effects. It also has a myriad of other effects, including preventing the migration of progenitor cells and inhibiting the formation of blood vessels necessary for the development of HO. As seen in the Palovarotene study, Rapamycin also resulted in significant reduction in heterotopic bone volume, and lower expression of genes related to cartilage and bone formation. Rapamycin is a powerful immune suppressant that could be contraindicated in a patient who is also battling infection, as it may prevent their body

from mounting an adequate response to the infection. Unlike Palovarotene, Rapamycin has been associated with minimal to no wound healing complications.

The third drug we tested is an antibiotic, Vancomycin. This antibiotic was chosen for its effectiveness against MRSA in particular. We hypothesized that if the addition of MRSA worsened the inflammation and HO formation, then treating the infection should reduce both. This turned out to be true but with some surprising results. First, in the injury model with MRSA infection, the addition of Vancomycin was able to completely eradicate the infection and significantly reduce the amount of HO formed. Interestingly, when the injury model was applied without the addition of MRSA, Vancomycin still resulted in significant reductions in the amount of HO formed. This indicates Vancomycin has other effects on HO formation than only clearing infection. This also means Vancomycin may have a broader application than we initially thought. We are currently investigating the mechanisms through which Vancomycin may be acting.

We are now in the process of designing experiments for additional therapies. These will include testing novel drugs developed specifically to inhibit HO formation as well as testing other drugs in combination. By using Rapamycin and Palovarotene in combination, we may be able to lower the dose of each drug and reduce the risk of harmful side effects while maintaining the effectiveness.

Our understanding and knowledge of heterotopic ossification has expanded dramatically over the past decade. More recent research has focused on treatment options that are safe and less invasive than surgical excision. Questions about side effects, practicality, and efficacy still remain. Even with all that we have learned, there is a long way to go before we will be able to transition the lessons we have learned in the laboratory to the men and women of our military. ✈

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# GUIDING LIGHT THROUGH HOLES:

Naval Applications of Hollow Core Fibers and Waveguides

FOR MORE THAN 30 YEARS, FIBER OPTIC CABLES HAVE CARRIED THE BACKBONE OF MUCH OF THE WORLD'S INFORMATION INFRASTRUCTURE. TODAY, THERE ARE NEW WAYS TO MAKE FIBER EVEN MORE EFFICIENT, WITH DIRECT IMPLICATIONS FOR A HOST OF NAVAL APPLICATIONS.

One only has to look back 30 years to a time when the fastest telecommunication that was available to residential customers was a telephone.<sup>1</sup> The limiting factor being the rate at which electromagnetic signals can be sent over copper wire (this rate is also known as the bandwidth or capacity). Although optical signals could carry information at much higher rates, they could only transmit over short distances either through the air or in primitive light guides with very high loss.

This changed with the invention of low-loss silica optical fiber in 1970,<sup>2</sup> which initiated a revolution in telecommunications capacity. An optical fiber works by forcing light to propagate in a layered glass medium consisting of a small core surrounded by a region known as the cladding, as illustrated in Fig. 1(a). The difference between the two glass regions is characterized by their refractive index, given the symbol  $n$  (this is the same property that causes light to bend when it enters water). When the core has a higher refractive index than the cladding, the light will be guided along the core by the mechanism of total internal reflection. This low-loss silica fiber with its extremely high purity is now capable of propagating light over one kilometer with a reduction of only four percent of its power (at a wavelength of 1.55 micrometers) and has led to an increase in available bandwidth of over five orders of magnitude and paved the way for modern telecommunication systems and the internet.

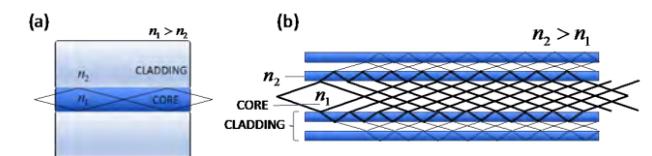


Figure 1: (a) Light guidance by total internal reflection in a conventional optical fiber, (b) Light guidance in a photonic crystal fiber.

By Drs. G.A. Cranch, R.R. Gattass, R.T. Schermer, and G. Beadie

Photo by Shutterstock

Despite the extraordinary benefits to telecommunication systems of propagating light in low-loss silica fiber, for other applications propagating light in solid media imposes limitations. Light is typically confined to a core only a few wavelengths in diameter resulting in very high intensity. High intensities interact with the glass causing an increase in loss and therefore limit the maximum power that can propagate. In addition, absorption in silica glass increases rapidly at wavelengths above 2.5 micrometers in the infrared, preventing its use above this wavelength. This isn't a problem for most applications that operate at wavelengths shorter than 2.5 micrometers, but some applications use other regions of the spectrum extending into the mid-wave infrared (2.5-5 micrometers) and long-wave infrared (8-12 micrometers). Other glasses, known as soft glass, do not exhibit this absorption and can be used to transmit infrared radiation above 2.5 micrometers, but absorption is still much higher than silica at the lower wavelengths.

The subject of this article is a new type of optical fiber that actually guides light through a small hole in the center of an optical fiber with low loss. When light is guided in this air core, many of the restrictions described above are avoided. However, what makes this difficult is that when light propagates in a glass pipe of this kind the condition required for total internal reflection is not met. Light propagating in a glass pipe will experience a core medium (air) with a lower refractive index than the surrounding material (glass) and rapidly leak out. To overcome this, an entirely different guidance mechanism must be employed to enable light to be guided over long distances with a very low loss.

A new guidance mechanism in optical fiber was proposed in 1996 that used a structure known as a two-dimensional photonic crystal.<sup>3</sup> Light at certain wavelengths is prevented from passing through such a structure in one direction, where it is reflected back in the direction it came but can pass through in a different direction. (Studies of these structures also were under way at this time at the Naval Research Laboratory [NRL].<sup>4,5</sup>) It was later shown that by surrounding a hollow core with a photonic crystal, light is prevented from escaping and is forced to propagate along the hollow core of the fiber,<sup>6</sup> as illustrated in Fig. 1(b). Here, an air core is surrounded by alternating layers of air and glass, which form the photonic crystal structure. To make these layered regions of air and glass (later referred to as microstructure), patterns of more small holes surrounding the core are formed that run the length of the optical fiber forcing the light to propagate through the center hole with no means of escape.

In addition to photonic crystal guidance, several other guidance mechanisms have since been demonstrated that have driven the new field of hollow core optical fibers. This article will describe research efforts in the optical sciences division at NRL that have applied this new technology to a range of naval-relevant applications offering solutions not previously possible with conventional optical fibers and waveguides.

### High-Power Infrared Light Guidance

Infrared countermeasures are used to protect aircraft from infrared-homing missiles by confusing the missiles' guidance systems. These systems require delivering high-power infrared radiation at wavelengths above 2.5 micrometers to remote locations on the platform. High absorption in silica at these wavelengths precludes their use for this application. Propagating the light in an air core surrounded by silica offers a potential solution. Although the silica material surrounding the core is lossy, most of the light is guided in the air core avoiding interaction with the lossy silica cladding. An even better solution, however, is to use a lower loss cladding material such as a soft glass. The combination of low-loss cladding material and light guidance in air offers overall lower propagation losses compared with other fiber designs. In addition, these have melting temperatures much lower than silica, making them easier to handle and form into structures.

The challenge comes in the form of how to fabricate such a fiber with the necessary microstructure (the holey region around the core) to enable low-loss guidance in the air core. This is overcome by using an extrusion method to fabricate the preform, a cylindrical glass structure that forms the basic building block of all optical fibers, where soft glass heated to its softening point is forced through a patterned die (like a cookie press) to create the preform. An example of a preform is shown in Fig. 2. Such a technique provides an extremely flexible and low-cost approach to making preforms with highly complex glass structures.



Figure 2: Soft glass based extruded preform.

To make the fiber, the preform is heated at one end and drawn down to the required diameter. This process retains the geometrical structure of the preform, producing a fiber that is a dimensionally scaled replica of the preform and thus contains the geometrical structure that includes the air core and surrounding cladding microstructure to enable light guidance. The microstructure surrounding the core provides the guidance mechanism, by ensuring that light cannot be scattered outside of the core, forcing it to propagate along the central hole using a design known as a negative curvature fiber.

End face images of fibers drawn using these techniques are shown in Fig. 3(a)-(d) illustrating a range of microstructure designs. The transmission loss over the wavelength range 2 to 12 micrometers is shown in Fig. 4 (blue trace). Strikingly, in the important window from 9.5 to 11.5 micrometers loss falls to as low as 2.1 decibel-milliwatts, which compares with 380 decibel-milliwatts (i.e., 38 orders of magnitude higher) if the light propagates in the bulk soft glass material (green trace).<sup>7</sup> The proposed design enables a single fiber to transmit both atmospheric windows in the 2 to 5 micrometer wavelength range and an additional band in the 8 to 12 micrometer range.

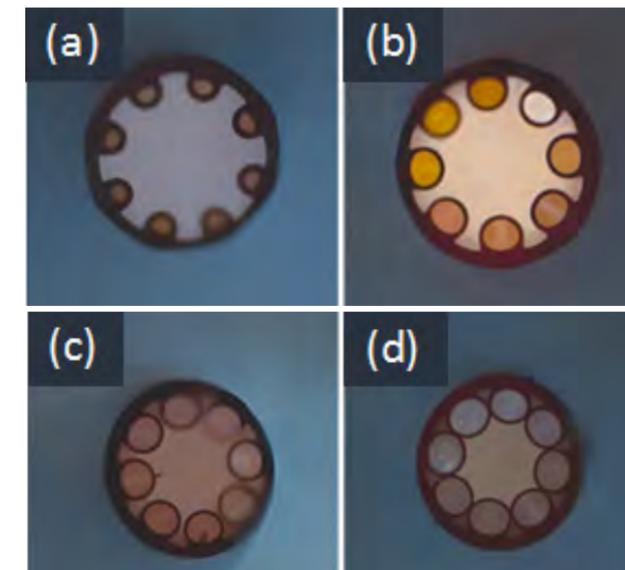


Figure 3: (a)-(d): Hollow core fiber with different cladding designs.

Soft glass-based hollow core optical fibers provide a previously unavailable means of delivering infrared radiation with low loss to locations remote from the laser source, an essential requirement for modern infrared

countermeasures systems.

### Measuring Magnetic Fields with Atoms of Cesium

The second application of hollow fibers involves the measurement of electromagnetic fields. High-precision magnetic and electric field sensors have many Navy applications ranging from detection of buried ordnance (both undersea and on land) to target detection. These sensors can be thought of as long-range metal detectors and these applications will benefit from new sensor technology and implementations that offer improvement in resolution, reduction in power consumption, and improved reliability.

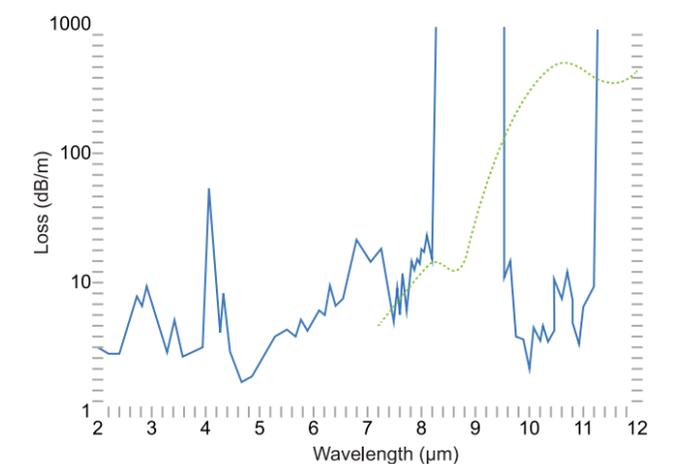


Figure 4: Transmission loss vs. wavelength for design (c). Blue trace is the transmission loss of hollow fiber and green trace is loss in bulk soft glass material.

One very high-resolution method to measure magnetic fields involves measuring the energy state of a magnetically sensitive atom. When certain elements are placed in an electric or magnetic field their energy states will experience a shift. Measurement of these shifts can enable a very high precision measurement of the external field.

First, the atom is prepared for the measurement by exciting it to a higher energy state with an optical beam, known as a pump, which is tuned in wavelength to interact with the atom. A single beam can excite a vapor of atoms into an excited state, known as a coherent state. When the pump beam is removed, the atoms release their energy in a characteristic way dependent on the external electromagnetic field. A second weaker optical beam, known as a probe, can be used to measure this behavior, enabling the external field to be measured to high

precision. Recent developments in compact laser sources and portable optical units have moved these technologies out of the laboratory and into practical, albeit highly specialized applications.

These measurements are performed on a vapor of atoms, which is usually confined inside a small glass cell. However, optical interaction with atomic vapors over short distances is very weak. This is where a hollow core fiber can help, by improving this weak interaction. The center hole of the fiber can be flooded with the atomic vapor and provide a very long interaction length with the optical beam. An illustration of this is depicted in Fig. 5(a), showing how pump and probe beams are injected into each end of the fiber.

Of course, nothing comes for free. When gases are confined into very small volumes such as the hole in a hollow fiber, they experience a large number of wall collisions because of their rapid motion. When the vapor is in an excited state, these wall collisions destroy the coherent state rendering the atoms useless for making accurate measurements.

Efforts are under way to reduce the effects of wall collisions by applying inert coatings to the inside wall of the fiber or by introducing inert buffer gases to slow down the atoms.<sup>8</sup> Fig. 5(b) shows part of the experimental implementation to flood atomic vapors into hollow core fiber. The end face of a vacuum chamber is shown containing hollow core fibers with a range of hole sizes. The chamber is flooded with cesium filling the holes of the fibers. Optical diagnostics are used to characterize the behavior of the excited cesium atoms inside the fibers. Fig. 5(c) shows an end face image of a silica photonic crystal

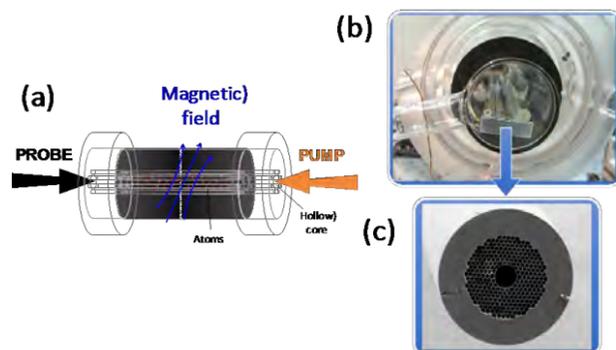


Figure 5: (a) Hollow fiber loaded with atoms, (b) looking in end face of vacuum chamber containing hollow core capillaries and fibers loaded with cesium vapor, and (c) end face image of hollow core fiber.

fiber used in these experiments.

In addition to enabling long interaction lengths, hollow core fibers also provide compatibility with conventional fiber needed to deliver the pump and probe signals. This would remove the need for free-space optical coupling leading to smaller and lighter delivery optics with improved mechanical robustness and reliability.

### Optical Limiters in Liquid-Filled Hollow Waveguide Arrays

A third application of hollow fibers involves their use to implement a device known as an optical limiter. This is a device intended to clamp transmitted optical energy to safe levels (i.e. its transmission efficiency decreases rapidly at high input energies) and can be used in a variety of applications to protect either human vision or imaging sensor technology from blinding or damage because of

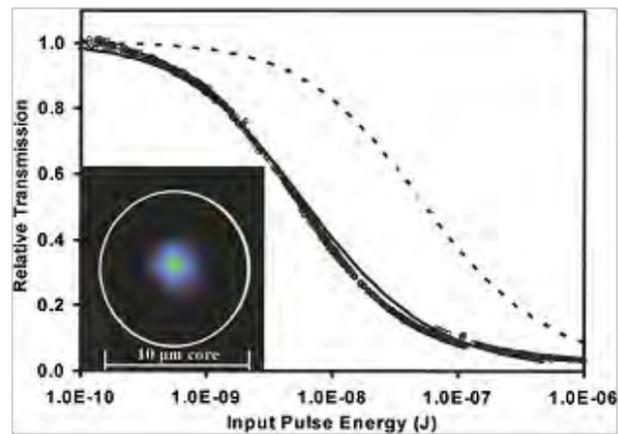


Figure 6: Relative transmission vs. input pulse energy for a single circular waveguide (circles = measurement; solid line = theory). (Inset) Radial intensity profile in waveguide.

high intensity optical radiation.

When light passes through certain liquids (known as nonlinear liquids) the absorption increases rapidly when the light intensity exceeds a threshold. If the center hole of a hollow fiber is filled with the liquid then the interaction can be dramatically increased between the light beam and the liquid. Such a technique has been utilized to enhance the performance of an optical limiter.<sup>9</sup>

Research conducted at NRL demonstrated that when light propagates in a hollow waveguide containing a nonlinear absorbing liquid, the nonlinear absorption is enhanced when compared with propagation through the same

length of bulk liquid material. The data shown in Fig. 6 demonstrate how the relative transmission efficiency (ratio of the measured transmission loss to the linear transmission loss) decreases with the input pulse energy (open circles are experiment and solid line is theory). The dashed curve shows the dependence expected if the intensity distribution were uniform across the waveguide. By comparison, the observed data represented by the solid curve illustrates how the nonlinear threshold is further reduced due to the extra confinement of the light (the inset of Fig. 6 shows how input light propagates with a mode size even smaller than the waveguide core further increasing the intensity).

This concept was extended to waveguide arrays filled with nonlinear liquid. Hollow core waveguides were made by stacking capillaries together in a close packed structure and drawing them down in the same way an optical fiber is drawn from a heated preform. End face images of three different arrays with different waveguide separations (when illuminated) are shown in Fig. 7.<sup>10</sup> These different waveguide geometries provide a means for tailoring the optical response for a given application. In particular, arrays like these with core-to-core separations matched

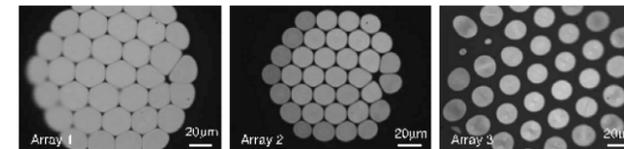


Figure 7: Images of illuminated arrays with different waveguide separations.

to the elements of a detector array, could be useful in sensor protection applications.

### Tunable Time Delays for Radio-Frequency Communication Links

A third application of hollow fibers relates to transmitting wide bandwidth analogue signals in an optical fiber. Terrestrial radio frequency (RF) transmission forms the basis of traditional analogue communication systems broadcasting radio and television signals over large areas. By transmitting these RF signals over an optical fiber, however, many of the additional benefits of fiber transmission can be harnessed such as low transmission loss, immunity to electromagnetic interference, and wider bandwidth as well as lower probability of interception. In addition, confining the RF signal to an optical fiber

prevents further contamination of the often congested RF environment.

Such a technique is implemented by encoding the RF signals onto the optical wave propagating in the fiber (for example by using the RF signal to modulate the intensity of the optical signal) to make an RF photonic link. Once encoded, the optical signal is transmitted across the fiber, and decoded at the receiver. Normally, this decoding is performed in the electronic domain, however, once the RF signal is encoded on an optical signal, signal processing can be applied to the RF signal without having to convert it to the electrical domain, leading to greater flexibility in signal control.

An RF photonic link of this kind uses a range of high-performance fiber optic components. One such component is a tunable delay line that imparts a controllable delay on an optical signal. In its simplest form, this can be implemented by bouncing the optical signal from a translatable mirror as illustrated in Fig. 8(a). Here, light is directed onto a mirror through an optical circulator and the reflected light is directed back onto an output fiber. Hollow core optical fiber can greatly extend this concept. A mirror is formed inside a hollow fiber by injecting a tiny droplet of liquid metal into the core as illustrated in Fig. 8(b). The location of the mirror can be adjusted by applying a pressure differential across the liquid metal using a pneumatic pump. The range of optical delay is now greatly extended as the hollow core fiber can be made very long. In addition to the large tunability of this device, this all-fiber implementation avoids mechanical

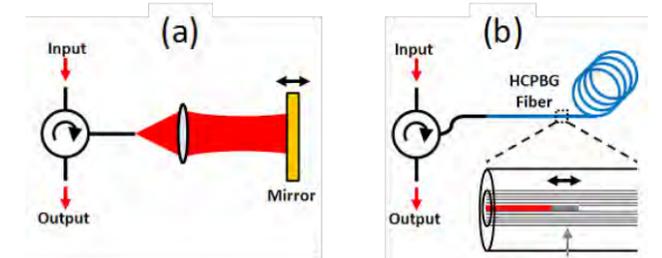


Figure 8: (a) Free-space delay line, (b) hollow core fiber based delay line.

instability and coupling losses associated with free space optics and improves overall mechanical robustness.<sup>11</sup>

Applications in the Navy for this technology vary widely. In addition to being a key component of wide bandwidth communication links, other more specialized applications include tunable microwave filters, phased array



beamformers, fast analog-to-digital converters, arbitrary waveform generators, signal correlators, and frequency converters and mixers.

### Measuring Tiny Displacements

The final application of hollow fiber relates to its use for measuring minute changes in length. One of the most sensitive techniques used to measure changes in length of an optical fiber is known as interferometry, where coherent light propagating in an optical fiber is combined with light propagating in a second fiber. Changes in the path length difference between the optical fibers cause a change in the relative optical phase that can be observed as a change in intensity in their combined output. This technique forms the basis of the optical fiber hydrophone, which measures changes in pressure through changes in length induced in the optical fiber. This technology was also developed at NRL, and has been applied to a range of military and commercial surveillance and monitoring applications (the fiber optic hydrophone was the first practical application of single mode optical fiber, preceding its use in telecommunication systems). Its success stems from the ability to measure fractional changes in length of optical fiber to the level of 1 part in  $10^{15}$  (a level surpassed only by gravitational wave detectors).

The smallest resolvable change in length that can be made with interferometry using standard solid glass optical fiber is limited by tiny fluctuations in the temperature of the glass caused by thermodynamic processes. Although these fluctuations are at the nanoKelvin ( $10^{-9}$  Celsius) level, they impose a limit on how accurately changes in length of the optical fiber can

be resolved and can limit the performance of some fiber optic hydrophone systems.

These temperature fluctuations are a fundamental property of the glass in which the light propagates and can only be avoided by propagating the light in a vacuum or gas. It follows that if the light propagates in the core of a hollow core fiber, it may be possible to overcome this limit and improve the performance of sensor systems. Recent work has shown that displacements in hollow core fiber can be resolved with higher resolution compared with propagating in a conventional solid core fiber.<sup>12,13</sup>

### Conclusion

This article has shown how a single technology can impact an extremely broad range of naval-relevant applications. This technology is just one of hundreds currently under development within the NRL's 6.1 basic research program.

A key role of the laboratory is the invention and development of advanced technologies for the US Navy that may not be found in university labs and commercial enterprises. The sustained commitment to Navy research and development that the NRL's 6.1 program provides will ensure long-term technological superiority of the fleet is maintained.

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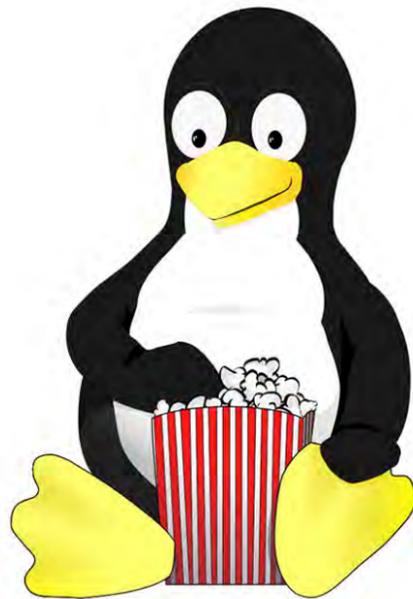
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# POPCORN LINUX: SOFTWARE FOR A DIVERSE WORLD

By Robert Lyerly, Christopher Jelesnianski, Anthony Carno,  
and Dr. Binoy Ravindran

**WITH MANY SYSTEMS RUNNING ON MULTIPLE—AND OFTEN VERY  
DIFFERENT—PROCESSORS, HOW DO YOU GET THEM ALL TO OPERATE  
TOGETHER EFFICIENTLY?**

In 1965, Gordon Moore famously predicted that the number of transistors, tiny electrical switches which form the processing logic in computers, would double inside an area of silicon every year. Later amended to a forecast of doubling every two years, Moore's law has continued to hold true for over half a century. In fact, development roadmaps from chip manufacturing giant TSMC show transistor shrinkages down to five

nanometers, or about 20 times smaller than a flu virus. Through most of the 1990s and early 2000s these extra transistors were transformed into exponentially increasing computational capacity. Much of the performance increase was due to the ability of processor designers to accelerate single-threaded code, the execution of a single line of instructions within an application.

In recent years, however, the ability to do additional useful work with those transistors has slowed because of physical limitations (such as heat dissipation and power consumption) and as well as how computers execute an application's instructions. This plateau could not have come at a worse time, as we have plunged headfirst into the age of big data and big computing. There is an insatiable need for more powerful computers in domains such as weather forecasting, disease epidemic modeling, business analytics, machine learning, and computer vision.

To continue increasing compute power, chip designers began duplicating processing units, known as processing "cores," within a single chip. For example, the iPhone 7 has four processing cores so that the phone can simultaneously execute foreground tasks (dialing phone numbers, opening a webpage) and background tasks (checking for new text messages, updating the Facebook news feed). Using multiple cores allows chip designers to put those extra transistors to good use, letting the phone squeeze out additional performance by executing independent work in parallel. More recently, chip designers have begun specializing processors for different tasks—for example, graphics processing units are designed to render graphics much faster than central processing units, but are worse at other types of tasks such as web browsing. Specialization is the key to further increasing compute power, and there are significant investments being made in alternative architecture designs such as programmable network interface controllers, field-programmable gate arrays, and digital signal processors. Future systems will be composed of heterogeneous processors, similarly to a Swiss army knife built from a variety of tools.

Programming these diverse heterogeneous processors is difficult, because they have physically separate components (e.g., data caches) and they use different instruction-set architectures (ISA). A processor's ISA is the set of instructions the processor understands, and defines the interface between the software and the hardware. One could think of a processor's ISA as the language it uses to communicate with the outside world. This means processors from Intel (found in laptops, desktops, and servers) that "speak" the x86 language do not understand the ARM language used in smartphones and embedded devices. Programmers must build their applications using the language defined by the processor's ISA to get the hardware to perform useful work.

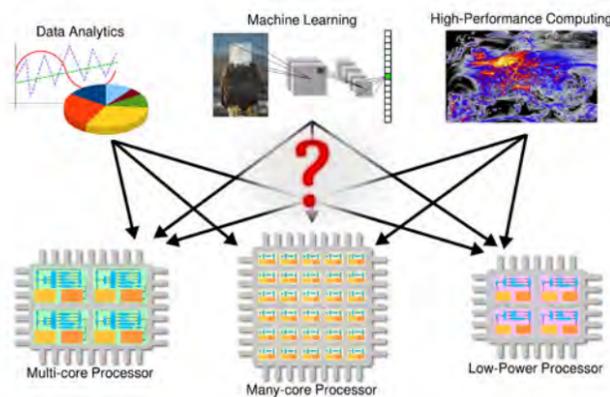
To program heterogeneous processors, developers have traditionally had to break their applications up into pieces that can run on separate ISAs and manually select the best architecture for a given program piece. Imagine writing a book, except you must find and write each chapter of the book in the language that requires the smallest number of words. This is obviously a tedious and highly error-prone process, especially as developers add new features to their applications over years and even decades. In addition, the architecture choices baked into the application by the developer may be sub-optimal if the processor is running multiple applications. This could cause significant performance degradation by overloading one processor in the system while another processor sits idle.

These emerging hardware trends pose a particular challenge for the Navy's enterprise-class software systems—which include combat system software such as the Aegis weapon control system—as they undergo hardware refreshes in their current and emerging code baselines. In particular, such legacy software systems are large (several million lines of code), have significant degrees of complexity (concurrency, distribution, fault-tolerance), and have received significant investment in resources in their development and maintenance. Because of their large size, complexity, and investment, such codebases are rarely discontinued. Instead, they are continuously enriched with new functionality, patched to add new security features, ported onto new hardware, and maintained over long life cycles. This begs the question: how can Navy developers take advantage of the benefits offered by next-generation heterogeneous processors without rewriting applications from the ground up?

The Popcorn Linux project (<http://popcornlinux.org>), spearheaded by Dr. Binoy Ravindran and the system software research group at Virginia Tech (<http://www.ssrp.ece.vt.edu>), aims to answer that question using a novel software infrastructure. The project is supported in part by the Office of Naval Research and NAVSEA/Naval Engineering Education Consortium as part of an effort to future-proof naval software systems. They recently published a paper at the 2017 International Conference on Architectural Support for Programming Languages and Operating Systems detailing how to push per-processor hardware and ISA differences down into the infrastructure software on which applications execute, so that developers can focus solely on the application logic. The Popcorn Linux project uses a modified version of the open-source Linux operating system, which powers

the vast majority of servers in datacenters as well as the popular Android smartphone. The Linux operating system is responsible for brokering access to the hardware in the system (your files, the internet, etc.), providing access for applications running on your computer. The operating system also is deeply intertwined with the underlying processor, as it must understand each processor's capabilities and quirks to run the system. The operating system is structured, however, so that applications do not have to understand these low-level hardware details—they simply use a standardized set of interfaces to talk to the operating system, which executes hardware requests on the application's behalf.

To allow applications to take advantage of heterogeneous processors, Popcorn Linux modifies standard Linux by running a separate instance of the operating system on each available ISA in the system. Separate instances of the Linux "kernel" (the core of the operating system with which applications interact) communicate and coordinate with each other. These kernels share information about the available hardware, which applications are running, and which applications should migrate between different processors. Applications running on this modified Linux use the same standardized operating system interfaces, but Popcorn Linux adds an extra layer of functionality that allow applications to request migration to other processors. When applications request access to a different processor, the operating system performs all the plumbing necessary to move the application and its data over to the new processor without any work by the application.

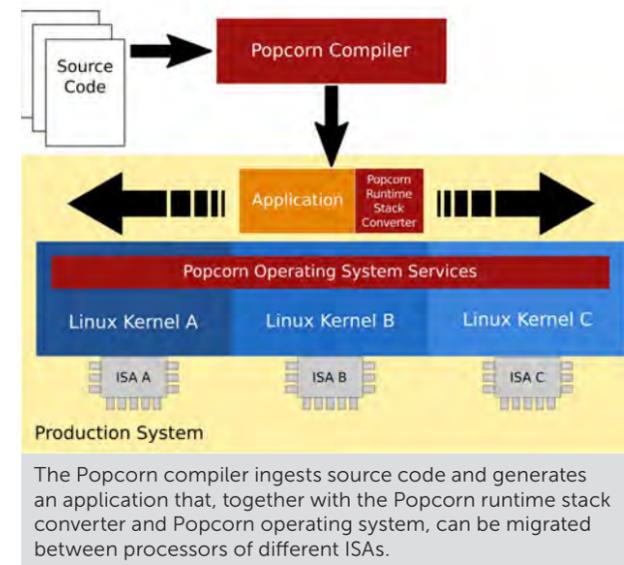


Emerging applications such as data analytics, machine learning, and high-performance computing consume ever increasing compute power. It is unclear, however, how these applications will run on new processors, which are diversifying in the face of diminishing returns in single-threaded performance.

Simply moving running applications between different processors, however, is not enough to transparently support heterogeneous hardware. Applications are built using a piece of software called a compiler, a tool that converts programming languages (human-readable languages in which programmers write their applications) into 1's and 0's that computers understand. The compiler is responsible for taking the high-level instructions specified by programmers and implementing them using the instructions the processor understands—the ISA. When an application is "compiled," the compiler generates a set of instructions specific to the processor on which the application is expected to run. In Popcorn Linux, a modified compiler generates these instructions for all available ISAs and arranges them so that the operating system knows how to find the correct version based on where the application is executing. Popcorn Linux includes a customized compiler based on LLVM, an open-source compiler used by many organizations including Apple, Google, and others.

The last piece of the puzzle relates to how applications execute on each different processor. Applications execute using a "runtime stack," a small amount of temporary data necessary to drive the application forward. When building the application, the compiler sets up the runtime stack based on capabilities defined by the ISA. This means that an application's runtime stack is customized for a single ISA and cannot be used as-is when running on other ISAs. To get around this issue, Popcorn Linux implements a small helper tool to convert the runtime stack between ISA-specific formats when migrating between processors. This helper tool is transparent to the application and is hooked in by the compiler at build time. When migrating, the tool attaches to the application, converts the runtime stack between ISA-specific formats, and then forwards the application to the operating system in order to migrate to a new processor.

Using Popcorn Linux, developers do not have to think about the details of how to migrate applications between heterogeneous processors—rather they only have to think about when to migrate. Developers do not have to manually copy data or switch between ISAs to continue execution, making it dramatically easier to experiment with and leverage different processors. Each processor has a design "sweet spot" tailored to certain types of application execution. Traditional Intel x86 processors found in desktops and servers are exceptionally good at running a small number of complicated tasks



extremely quickly. More recently, manufacturers such as Qualcomm and Cavium have designed high-core-count ARM processors that excel at running many simpler tasks in parallel. Oftentimes applications may contain a combination of characteristics, meaning some pieces of the application are more suitable for one processor while other pieces are more suitable for another. Popcorn Linux enables developers to easily take advantage of the available heterogeneity in the system. Further research aims to remove the need for developers to select an architecture altogether—the system would analyze how applications execute and automatically select the most appropriate processor for the program.

In their paper, the Popcorn Linux team showcases a heterogeneous system containing Intel's high-performance x86 central processing units and Applied Micro's low-power ARM central processing units. After installing Popcorn Linux on the system, they evaluate running and migrating a set of applications versus a traditional single-ISA setup (i.e., containing two x86 central processing units). The results show that by using Popcorn Linux, datacenter operators could potentially achieve a 30-percent reduction in energy consumption by using the low-power ARM processor in conjunction with the high-performance x86 processor. The results hint that different combinations of heterogeneous hardware will allow developers to hit different design points—developers can pick and choose the hardware that best suits their needs, all without having to rewrite their applications.

Popcorn Linux's benefits also apply to legacy naval applications without requiring thousands of man-hours to rewrite millions of lines of code. Programs such as the Aegis Weapons Control System can be migrated onto heterogeneous-ISA hardware with very minimal changes to source codes. This can yield significant savings in maintenance costs, the biggest cost driver in the software life cycle. In addition, the Popcorn Linux software stack can enhance application performance, which can result in significant improvements in many Aegis-specific metrics such as enhanced target tracking and faster engagement times. Popcorn Linux also could be used for security purposes—traditionally, attackers exploit application flaws to gain control inside of an already-running application. These exploits are most often specific to the ISA on which the application is executing. By switching between ISAs, would-be attackers and their hand-crafted exploits would be rendered useless. Using Popcorn Linux, Navy system administrators would be able to detect and react to attacks on the system.

The future of processor design is heterogeneous. Processor designers have begun creating specialized chips tailored to different types of tasks, but programming heterogeneous computer systems today is tedious and difficult for developers, especially for organizations such as the Navy that have a significant legacy code base. To enable easier application development and allow legacy applications to exploit the benefits offered by next-generation processors, the Popcorn Linux project moves ISA handling down into the software infrastructure. Applications can seamlessly take advantage of the benefits without the headaches of complex software design. This will allow the Navy to future proof software for future hardware refreshes.

**About the authors:**

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# IDEAS MATTER AT THE WARFARE CENTERS: AN INTERVIEW WITH Dr. John D. Burrow

By Nicholas E. Malay

The anechoic flow facility is prepared for a test at the Naval Surface Warfare Center Carderock Division in West Bethesda, Maryland.

Photo by Steven Garafalo

## NAVAL SEA SYSTEMS COMMAND'S WARFARE CENTERS ARE AT THE INTERSECTION WHERE RESEARCH, ENGINEERING, AND WARFIGHTING MEET.

**T**echnical innovation has historically given the Navy and Marine Corps a decisive edge when it comes to combat capability. But whether it's a radical new ship design, advanced weaponry, or other technological achievement, it all began with just an idea. And ideas need research to take root.

Dr. John D. Burrow, who recently retired as the deputy assistant secretary of the Navy for research, development, test and evaluation, was responsible for oversight and stewardship of the Department of the Navy's Naval Research and Development Establishment (NR&DE). He also helped champion the Navy and Marine Corps' understanding of basic science and its ability to help develop future naval warfighting capabilities.

Burrow recently discussed the role Naval Sea System Command's warfare centers play within the NR&DE in supporting the Department of the Navy's efforts to retain and grow its technological advantage and maritime superiority.

**Q:** How do you describe the role and importance of basic scientific research for the Navy?

**A:** When I think of basic research, I'm thinking of pure science most of the time. When I think of applied research—and the advanced technology development and then what we call the advanced component development and prototype—that's more of a technology maturation leading to something that needs to be designed or engineered for a ship, aircraft, or submarine.

We know that basic research is in the "discovery" area. And it may take decades for basic research to evolve into applied research for some of our future technologies. Basic research is the ability of scientists and engineers to pursue new ideas and new concepts—kind of like the pursuit of learning—in the hopes of finding something that may eventually transition into a future naval capability.

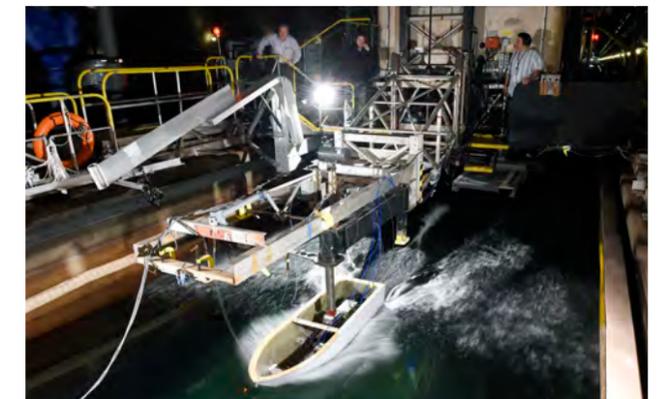
**Q:** How important is it for the Navy to devote time and resources to basic research?

**A:** From a Navy and Marine Corps point of view, we hope our investments in basic research produce fruits that are going to pay off later. But we also recognize that these are, in some cases, "needles in the hay stack" kinds of searches: in some cases they will pan out, in other

cases they may contribute to a larger intellectual bank, both for the DoD [Department of Defense] and even the commercial community as a whole. At the basic research area, freedom of maneuver is essential. Scientists and engineers have an idea, they have a hunch, they want to explore or discover something based on others research or ideas. Certainly, something they believe will lead to a major breakthrough, concept, or idea.

**Q:** How do the scientists and engineers of the Naval Sea Systems Command warfare centers fit into the Navy Research and Development Establishment?

**A:** They are a key element. The scientists and engineers at NUWC [Naval Undersea Warfare Center] and NSWC [Naval Surface Warfare Center] in particular, really provide the backbone of our undersea and surface engineering development work that is a key component of developing future naval warfighting capabilities. That said, it's incumbent upon those scientists and engineers to build relationships with organizations like Space and Naval Systems Center Pacific and Atlantic, the Naval Research Laboratory, and the naval air warfare centers. Having a community of intellect, a community of real technical exchanges is critical. It's critical realize the full potential of our future Navy and also to realize the full potential of these organizations—both at the facilities and within the workforce. With the advent of Navy Digital—especially over the next 30 or 40 years—there is a speed of learning that is going to take place in our academic



A ship hull model attached to a high-speed carriage moves through waves at the Naval Surface Warfare Center Carderock Division's David Taylor Model Basin. The project's purpose is to study the fundamental physics of the water impact of high-speed planing hulls and to measure the slamming loads and resulting motions of the craft upon re-entry into the water. (Photo by John F. Williams)

and commercial communities that will have a direct applicability to naval warfighting. We have to not only be a part of that, but, in many cases, we need to lead that. And the best way to lead that is through developing smart people—people who are actually doing or involved in basic research leading to applied research and ultimately, technology development, and prototyping.

**Q:** What is the danger with trying to rapidly transition technical capabilities too soon?

**A:** Since the beginning of Naval Innovative Science and Engineering [NISE]/Section 219 certainly, the investments that we have made in basic research have not had the time to mature to the next level. [Since 2009, this program allows funding for cross-organization, multidisciplinary teams to mature technologies and transition them to the fleet.] The important take away is that it takes time to mature, to get to a point that the technical capability can be rapidly transitioned to solve a naval problem. So, the analogy I give is this: it takes 21 days for an egg to hatch. Now, the egg may be able to hatch earlier, a few days earlier, but if you want a chicken in seven days, you get an omelet, not a chicken. My point in saying that is there is truly a push sometimes to transition long before the capability is mature enough to transition.

There are absolutely immediate needs of our operational forces today. We, as a technical community across the

Naval Research & Development Establishment, and that includes the warfare centers, we have to be able to respond to those needs quickly. In order to do that quickly we have to have world-class scientists and engineers who understand where technology is today, how quickly we can transition that technology, and where that technology falls short or where it's a stop gap until more advanced science can be brought to the table. We need our technical community to be smart on all of this.

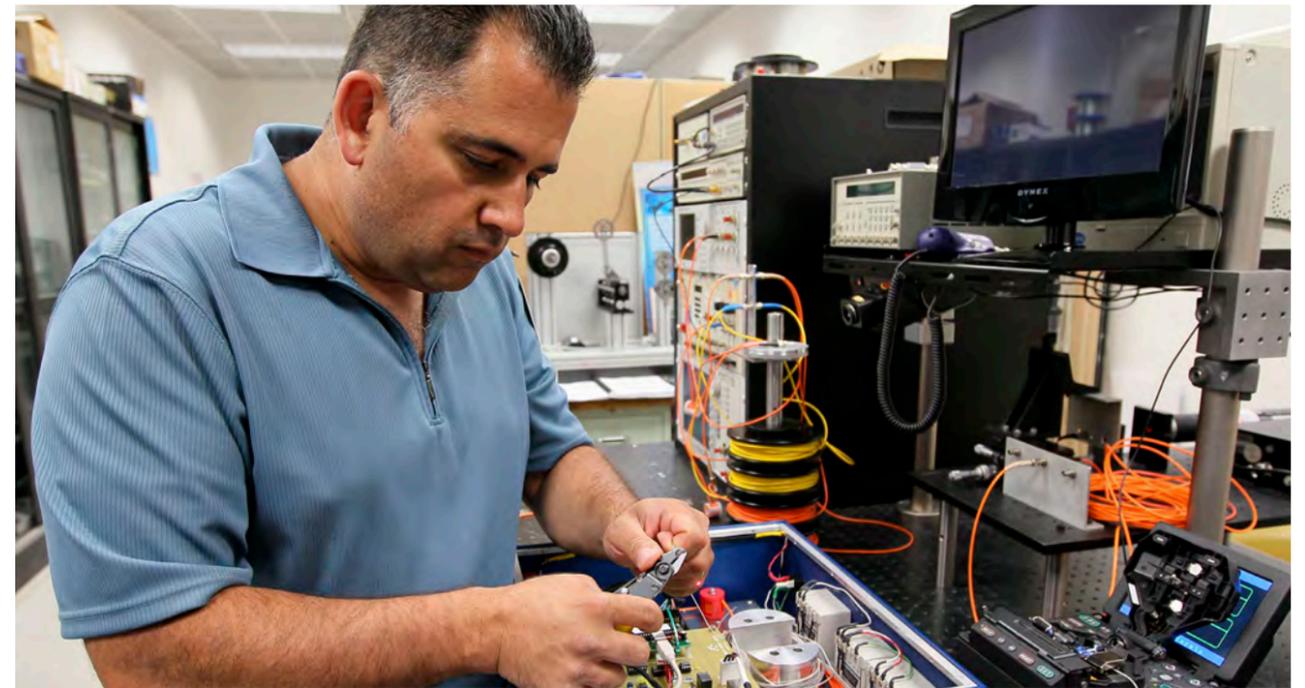
**Q:** If you had the chance to speak to each person in the NR&DE, what would you say to them about the value of basic research?

**A:** If we talk about basic research—or any technical capability—in isolation, then people will think about them in isolation. This is a continuum; this has to cover all areas, not just a portion of the continuum. Our leadership, our technical community, programmatic and acquisition community—we all have a stake in this, and all have to make sure we recognize both the needs and investments required in order to sustain the Navy and Marine Corps.

Basic research is key to the discovery of future capabilities, but basic research is not something that everybody is capable of doing, or should do. Our scientific and engineering community depends on discoveries in the 6.1 area, but for the most part, at NUWC and at NSWC most of the real research and development work spans



The latest electromagnetic railgun testing facility at Naval Surface Warfare Center Dahlgren Division carries on a tradition of ballistics and gunnery research and testing since World War I. (Photo by John F. Williams)



Lance Doddridge, an electrical engineer and physicist at Naval Surface Warfare Center Corona Division in Norco, California, splices fiber optic cable as he works on a calibration device used at the Naval Undersea Warfare Center Newport Division. (Photo by Greg Vojtko)

the 6.2, but more 6.3, 6.4, and 6.5 areas. And that's where their real contribution exists because now they can take and very rapidly develop new technologies or transition mature technologies into legitimate and needed warfighting capabilities.

Every time that I go out and ask the warfare centers as a whole, "do you have a solution to this problem?" I get feedback, for the most part, that contains a significant part of a NISE/219 investment. This investment is absolutely critical for our scientists and engineers to be able to go and independently develop new concepts and capabilities. The freedom that NISE/219 gives, in terms of new ideas and the pursuit of their own ideas, is important and fundamental to what the mission and responsibilities of our warfare centers are.

**Q:** With freedom comes opportunity, right?

**A:** Because of the trajectory associated with that new science or new technology, we have to be the ones at the very front who are continuously learning along the way. That's because it's our own team that can pick this thing up and say "Hey, this is ready, now let's go." It's the technical community that has to make those judgments.

Our scientists and engineers within our warfare centers have to have hands-on work, they have to be doing science and technology development and engineering that spans the full-spectrum of research and development. When I say that, I mean from 6.1 all the way to 6.5 through 6.7. Not only do they have to be given the opportunity to do that work, they have to be given the tools and facilities in order for them to be effective at doing that work. It's not only an opportunity for us to learn and discover, but also an opportunity to recruit and retain the scientists and engineers that really want to provide a service to our nation, and our Navy and Marine Corps.

They expect the opportunity to chase freedom of thought to go and discover new things, to pursue new ideas, and do it in such a way that they have the tools and facilities that can accommodate their needs. That is the responsibility we have and a key enabler to build our future naval capabilities. ✈

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## SOARING TO NEW HEIGHTS IN **WEATHER PREDICTION**

By Dr. James D. Doyle, Dr. David D. Flagg, Dr. Teddy R. Holt, Dr. Daniel P. Tyndall, Dr. Clark M. Amerault, Daniel Geiszler, and Tracy Haack

**UNMANNED AERIAL SYSTEMS, SUCH AS THIS SCANEAGLE DURING AN EXERCISE OFF THE COAST OF VIRGINIA IN 2013, CAN COLLECT CRITICAL METEOROLOGICAL MEASUREMENTS IN DATA-SPARSE REGIONS AND OTHER AREAS OF INTEREST.**

**E**nvironmental conditions in the marine atmospheric boundary layer (MABL)—the part of the atmosphere closest to the ocean surface—is notoriously challenging to predict due, in part, to strong horizontal and vertical gradients. Unfortunately, there is a paucity of environmental observations of this boundary layer in the littoral, particularly in tactically significant locations. Unmanned aerial systems (UASs)—now with a variety of capabilities and widely available—can be environmental platforms of opportunity to collect key MABL and air-ocean interface environmental information. Because UAS data may often be the only observations in a tactical region, understanding the effect of these observations in the littoral on environmental forecasts is vital to assess future mission planning and flight and ship safety forecasts, and to optimize asset allocations.

One component of the Trident Warrior exercise conducted off Norfolk, Virginia, in July 2013, was focused on the prediction of environmental conditions within the MABL that affect electromagnetic (EM) propagation. The propagation of EM radiation is subject to refraction because of changes in the vertical structure of temperature, moisture, and pressure in the atmosphere. The presence of a low-level temperature or moisture inversion can generate a condition of positive refraction whereby EM radiation emitted below the inversion may refract back toward Earth, extending the normal range of propagation beyond the horizon/line of sight. The timing, location, strength, and depth of inversions and anomalous propagation conditions are important characteristics of the environment that can inform ship navigators on expected performance of their sensors.

A suite of observations was deployed during Trident Warrior, including a Boeing-Insitu ScanEagle UAS equipped with research-quality instrumentation developed by Scripps Institution of Oceanography and capable of accurately observing within and above the littoral MABL. Seven UAS flights, each of several hours duration, were launched from R/V *Knorr* (AGOR 15) with this instrumentation payload over four days to measure meteorological quantities from near the surface up to 1,550 meters above mean sea level. These seven flight tracks are shown in Fig. 1. The campaign also included observations from instruments deployed in the vicinity of the UAS launches, including radiosondes, buoys, unmanned surface and underwater vehicles, and airborne expendable bathythermographs deployed from a P-3 aircraft.



Figure 1: Flight paths of the seven UAS flights taking meteorological observations during Trident Warrior 2013. The scale of the background figure varies; the length of the longest runway at the airfield pictured in the lower-right of the background image (Naval Air Station Oceana) is approximately 3.7 kilometers in length. The helical flight patterns extend up to approximately 1,550 meters above mean sea level.

The Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®), developed by the Naval Research Laboratory (NRL), is applied in a mode that includes two-way interaction with the Navy Coastal Ocean Model (NCOM), along with the NRL Atmospheric Variational Data Assimilation System (NAVDAS) customized for UAS assimilation. The data assimilation system allows us to quantify the impact of UAS observation assimilation on short-term model forecasts. In this application the finest horizontal resolution is 1.33 kilometers in the atmospheric model and 3 kilometers in the NCOM ocean model. During the Trident Warrior experiment, two different real-time COAMPS forecasts of 36 hours in duration were executed four times daily to assist with the mission planning. One real-time forecast was conducted without assimilation of any UAS observations, and a second made use of the ScanEagle observations of temperature, moisture, winds, heights, and pressure. The two model forecasts successfully highlighted the effect of the UAS observations in real time, satisfying one of the key objectives of the exercise. Here we highlight results from the same two types of forecast experiments conducted after Trident Warrior, which allows for the assessment of the effect of quality-controlled ScanEagle observations on COAMPS forecasts.

Radiosonde measurements taken in the vicinity of the ScanEagle flights provide the largest independent source to verify the COAMPS forecasts and quantify the effect of UAS observations. The results show that with assimilation of the UAS observations, marked improvement in statistical error, particularly with respect to water vapor mixing ratio prediction, occurs near the top of the marine atmospheric

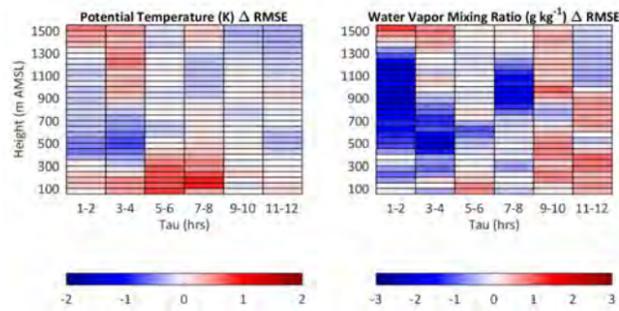


Figure 2: The difference in model root-mean-squared-error (RMSE) of potential temperature (left) and water vapor mixing ratio (right) between the case with UAS data assimilated and the case without UAS data assimilated. Decreases in RMSE are shaded in blue (increases in red) and represent decreased (or increased) model error due to UAS data assimilation. The RMSE is calculated from all available model-measurement comparisons within 50-meter vertical bins representing geometric height above mean sea level.

boundary layer using the radiosonde observations as truth (Fig. 2). Comparison of the atmospheric vertical profiles from radiosonde measurements against model-predicted fields reveals that the local bias reduction in model-predicted temperature and water vapor mixing ratio is shown at times to exceed 1 degree Celsius and 3 grams/kilogram, respectively. These broad improvements to model forecasts are found to be particularly strong at forecast lead times from one to approximately six hours.

Further investigations into the impact of UAS data assimilation on MABL prediction show a general improvement in the prediction of the vertical position and depth of the

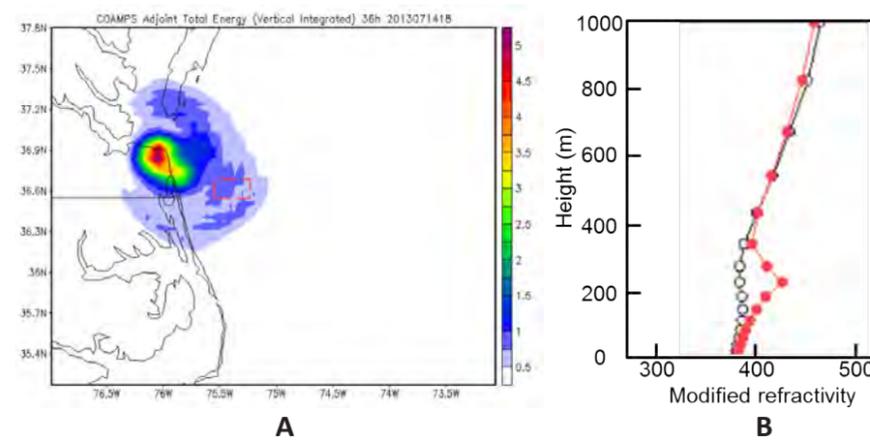


Figure 3: a) Vertically integrated total energy based on the adjoint optimal perturbations for 00 UTC, 16 July 2013. The response function is based on the vertical gradient of the modified refractivity. The region over which the response function is applied is shown in red and the position of the Knorr is denoted by the black circle. b) Vertical profiles of the modified refractivity (M-units) for the control (black) and perturbed (red) valid at 09 UTC, 16 July 2013. Note that the perturbed forecast of the refractivity makes use of the adjoint-based perturbations.

temperature and water vapor mixing ratio inversion that typically accompanies the top of the MABL. Where an inversion was identified from radiosonde profiles, the average observed base height and depth of the MABL inversion was approximately 250 and 130 meters above mean sea level, respectively. Profile comparisons reveal an average error reduction of model-predicted inversion base height and depth of approximately 30-35 meters using the radiosonde observations as truth. Results also show improvement to the model prediction of inversion strength, measured by the change of temperature or water vapor mixing ratio across the inversion. The average observed MABL temperature (water vapor mixing ratio) inversion strength during the campaign was approximately 2 degrees Celsius (4 grams/kilogram). The average error reduction in model-predicted temperature (water vapor mixing ratio) inversion strength is found to be approximately 0.4 degree Celsius (0.7 grams/kilogram). These average error reductions in the predicted shape and position of the MABL inversion demonstrate a potential for UAS data assimilation to yield substantial improvement in the prediction of the MABL inversion, a feature of broad influence to EM propagation, aerosol dispersion, and cloud development.

Improvements to the prediction of temperature and moisture profiles through assimilation of UAS observations also yield improved modified refractivity (M) profiles and, thus, more accurate diagnosis of refractivity conditions. Where the M-profile decreases with height, a trapping condition exists creating an invisible "duct" that allows EM signals to propagate further than under normal conditions.

These EM ducts and the propagation loss of EM signals in general may vary significantly over short distances due to turbulent motions in the atmosphere and changes in sea-surface temperature among other factors. The performance of the coupled model system in predicting EM ducts therefore depends in part on how finely it resolves the lower atmosphere in the vertical dimension. During two periods in the first half of the campaign, improvement to the prediction of M-profile shape and near-surface M values from UAS data assimilation yields substantially improved propagation loss prediction (error reduction of

approximately 25-50 decibels, using the radiosonde profiles as truth). During the latter half, model vertical resolution appears to impede improved diagnosis of the change of M with height. Further investigations are under way to better understand how the coupled system may be optimized for the prediction of EM signal propagation loss and EM ducts.

An adjoint model, which is technically the transpose of the forward tangent propagator of the forecast model, allows one to find the initial state sensitivity to a metric (kinetic energy, rainfall, etc.) at a particular forecast time over a specified region, referred to as a response function. A high-resolution (three-kilometer) nested adjoint modeling system is applied to the Trident Warrior observing period, with the vertical gradient of the modified refractivity used as the response function. Optimal perturbations are constructed from these adjoint gradient calculations with initial magnitudes comparable to analysis errors to investigate the growth of structures that are relevant for the predictability of modified refractivity conditions. An example of a typical sensitivity pattern is shown in Fig. 3a, which shows the vertically integrated total energy based on the adjoint optimal perturbations for 00 UTC, 16 July 2013, for a three-hour forecast. The region over which the response function is applied is shown by the red box. The adjoint shows a maximum in the sensitivity just to the northwest of Knorr. The shaded region highlights where the initial conditions are most sensitive for forecasts of the vertical gradient of modified refractivity. Fig. 3b shows a profile of the modified refractivity valid at 09 UTC, 16 July. By perturbing the initial conditions in the shaded region shown in Fig. 4a based on the adjoint sensitivity, the vertical gradient of the modified refractivity is changed dramatically into a state that supports an elevated EM duct. The adjoint results emphasize the importance of accurately observing the low-level water vapor and temperature.

Additional experiments were conducted with the COAMPS observation impact system to further quantify forecast improvement associated with UAS observation assimilation. The observation impact system maps COAMPS adjoint sensitivity fields into observation space using the adjoint of NAVDAS. For these experiments, a 12-hour forecast error using a modified refractivity metric was calculated in an area off the coasts of North Carolina and Virginia in the lowest one kilometer of the model's domain. The forecast error was used to force the COAMPS adjoint integrations. The resulting sensitivity fields were passed to the NAVDAS adjoint model to produce observation impacts. The percentage of error reduction attributable to the main observation types assimilated by NAVDAS is

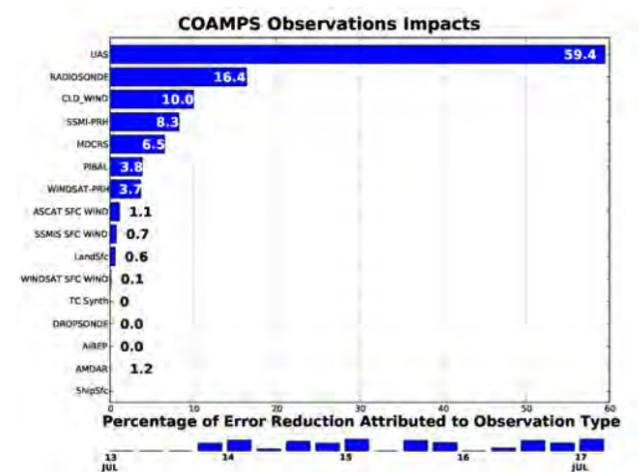


Figure 4: The percentage of 12-hour COAMPS forecast error reduction during Trident Warrior in modified refractivity space attributed to each observation type assimilated by NAVDAS. The forecast error was calculated in the lowest one kilometer of the model's domain over an area including the coastal waters of North Carolina and Virginia.

shown in Fig. 4. Results indicate that the UAS observations have an overwhelming influence in reducing short-term low-level refractivity forecast errors in the area of interest. Almost 60 percent of the error reduction is due to the UAS observations.

The assimilation of meteorological observations taken by a Boeing-Insitu ScanEagle UAS into the Navy's coupled numerical weather prediction system is shown to yield significant improvement in short-term prediction (one to six hours) of temperature and moisture, particularly in the vicinity of the top of the MABL. Improved prediction of temperature and moisture profiles supports improved prediction of modified refractivity, with direct impacts on prediction of EM signal propagation. These results highlight the promising potential for the assimilation of high-quality UAS observations to improve short-term environmental forecasts in the littoral zone in support of DoD missions.

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# SPATIAL RADAR ARRAY PROCESSING BELOW THE NYQUIST RATE

By Dr. Hatim F. Alqadah, Dr. Dan Scholnik, and Jean de Graaf

**MODERN ELECTRONICALLY STEERED RADARS CAN ENGAGE MANY MORE TARGETS MORE QUICKLY THAN THEIR OLDER MECHANICALLY STEERED PREDECESSORS. NEW RESEARCH IS LOOKING INTO RADAR ARRAYS FEATURING A VERY SMALL NUMBER OF INDIVIDUAL ANTENNA ELEMENTS THAT CAN EMULATE THE PERFORMANCE OF A MUCH LARGER ARRAY THROUGH NONLINEAR PROCESSING.**

**M**odern radars make use of electronically steered antenna arrays whose speed and flexibility will continue to play a critical role in assuring access to the battle space. Unlike traditional mechanically steered radars, which typically require seconds to complete a scan, antenna arrays can effectively steer a beam to an arbitrary position within the span of microseconds. By interlacing tasks in time, arrays exploit this dramatic increase in speed to detect and track multiple targets as well as provide multifunction radar capabilities. On receive; there are two major array processing functions relevant to radar: direction-of-arrival (DOA) estimation, and adaptive beamforming. In DOA estimation, the objective is to determine the number of signals contributing to the total antenna's response as well as their incoming directions relative to the array's orientation. In adaptive beamforming, the objective is to enhance the signal-to-interference-plus-noise ratio (SINR) of an array—i.e., to adapt the array's beam pattern to focus on signals of interest while simultaneously suppressing sources of interference.

Performance characteristics relevant to array processing include scan coverage, resolution, and side-lobe levels. More specifically resolution refers to how finely two sources can be distinguished from each other, and side-lobes refer to the height of any local maximas occurring in the array receive pattern other than the main beam or look direction. The geometry of the array, including the number and physical placement of the individual elements, has a major effect on these characteristics. For example, conventional array theory tells us that the resolution of an array is inversely proportional to its spatial extent (aperture). Therefore, to get better resolution, the array must span a greater area. At the same time we are restricted on how far we can space the elements from one another in order to assure unambiguous scan coverage.

We can see this by considering a plane-wave source with wavelength  $\lambda$  that is incident upon a uniform linear array (ULA), in which all receiver elements are positioned along a line with a uniform interelement distance  $d$ . ULA examples are shown in the top and bottom plots of Fig. 1. The field of view (FOV) of a line array can span over  $\pm 90$  degrees from array normal and its spatial extent would be its length, which for a ULA is proportional to the number of individual elements. When  $d \leq \lambda/2$  the beam pattern of the ULA will have a single main lobe within the FOV, as shown in the blue curve of Fig. 2. For higher  $d$  multiple grating lobes, which are local maximas with the

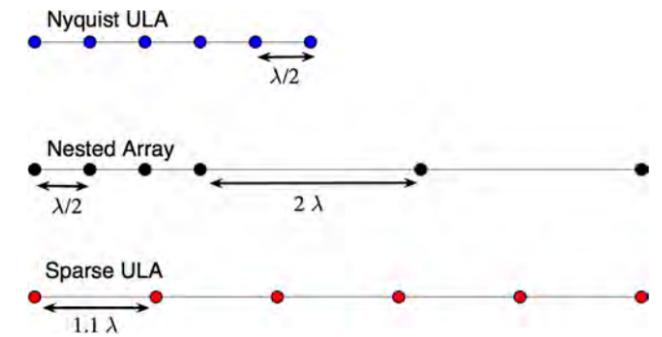


Figure 1: Array geometries of a Nyquist ULA (blue), a sparse ULA (red), and an example of nonuniform sparse array known as a nested array (black).

same height of the main lobe, can appear due to spatial aliasing, which is shown in the red curve of Fig. 2. These additional lobes can cause directional ambiguity unless additional a priori information is available. Thus  $d \leq \lambda/2$  is the spatial equivalent of the famed Nyquist sampling condition, which states that a signal must be sampled at a rate equivalent to at least twice the highest frequency contained in that signal.

As future Navy operational needs will increasingly rely on air and surface autonomous systems equipped with a plethora of other intelligence/surveillance/reconnaissance sensor hardware, next-generation arrays will face a challenge to balance electromagnetic performance with the associated restrictions on weight, power consumption, and size. To meet these requirements, it will be necessary to limit the number of elements in the array. For arrays with uniformly spaced elements satisfying the Nyquist

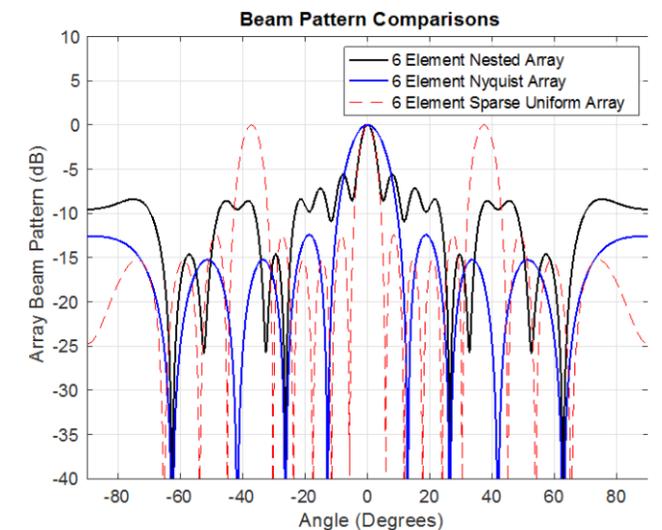


Figure 2: Showing the different beam patterns of a Nyquist ULA, a sparse ULA, and a nested array.

criteria, a restriction on the number of elements can result in poor spatial resolution characteristics. There are two approaches for increasing the aperture for a fixed number of elements. We can increase the interelement spacing  $d$ , uniformly violating the Nyquist criteria. Alternatively, we can nonuniformly position the elements, in which case only some of the interelement spacings will violate the Nyquist rate. These are both examples of sparse arrays, where the average spacing is greater than the Nyquist limit. A uniformly spaced sparse array will effectively place a restriction on the FOV because of the presence of grating lobes. For certain nonuniform sparse arrays, however, the grating lobes can be eliminated without requiring any restriction in the FOV. An example of such is a (two-level) nested array, which can be thought of as a joining together of two ULAs each with different spacings. Referring again to Fig. 2, we can see that a nested array exhibits a narrower mainlobe than that of a dense Nyquist array but without the grating lobes of the sparse ULA.

### Nonlinear Signal Processing with Sparse Arrays

Our research is focused on processing techniques for certain types of nonuniform sparse arrays whose element positions are integer multiples of a minimum interelement spacing, typically  $d = \lambda/2$  and such that the collection of all unique distances between elements taken pairwise is the same as for a larger Nyquist sampled ULA. The set of such pairwise distances is known as the difference coarray, and the number of occurrences for each element in this set is known as the element weight. Note that this definition of weights differs from the element weights that are normally associated with linear beamforming. An early example of such a nonuniform sparse array is the minimum redundancy array (MRA).<sup>1</sup> More recently, other configurations have emerged including nested arrays and coprime arrays, which is another way of combining two Nyquist arrays to form a longer sparse array.<sup>2,3</sup> An MRA has the fewest redundant pairwise distances (the sum of all weights for the difference coarray is minimal). Nested and coprime arrays have slightly more redundancy in their difference coarray, but both have a

relatively simple way of calculating the element positions. The difference coarray along with the associated weights for a Nyquist ULA, a sparse ULA, and a nested array are shown in Fig. 3.

There have been a number of techniques proposed for processing with such sparse arrays.<sup>4,5,6,7</sup> Traditionally, array signal processing approaches are based on an assumed linear model; that is the data is measured at the physical positions of the array and is linearly related to each source's voltage and phase. However, in the far-field the underlying mathematical structure of the measurement operator in conjunction with the particular element positioning of the aforementioned sparse geometries also yields a linear relationship between each source's intensity to the intensity observed at sensor positions of a virtual ULA. The virtual sensor positions are in fact the elements of the difference coarray. In other words, many of the advanced signal processing techniques that have been traditionally applied to Nyquist ULAs can be potentially applied to the virtual array. Looking at the difference coarray for a nested array in Fig. 3, we see that not only is the virtual array twice as long as the physical array, but seemingly we have many more elements. This means the virtual array would not only potentially exhibit superior resolution but there also

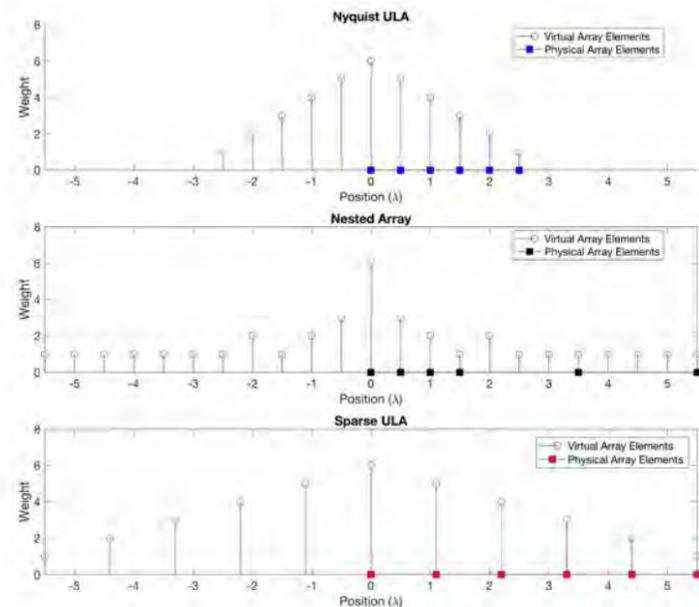


Figure 3: Illustrating the difference co-array generated from three different types of six-element linear arrays. The color square markers indicate the true physical position of the elements, while the circles indicate the positions and weights of the corresponding virtual array. The vertical lines in each of the figures refer to the weights, which yield the number of reoccurring spatial lags.

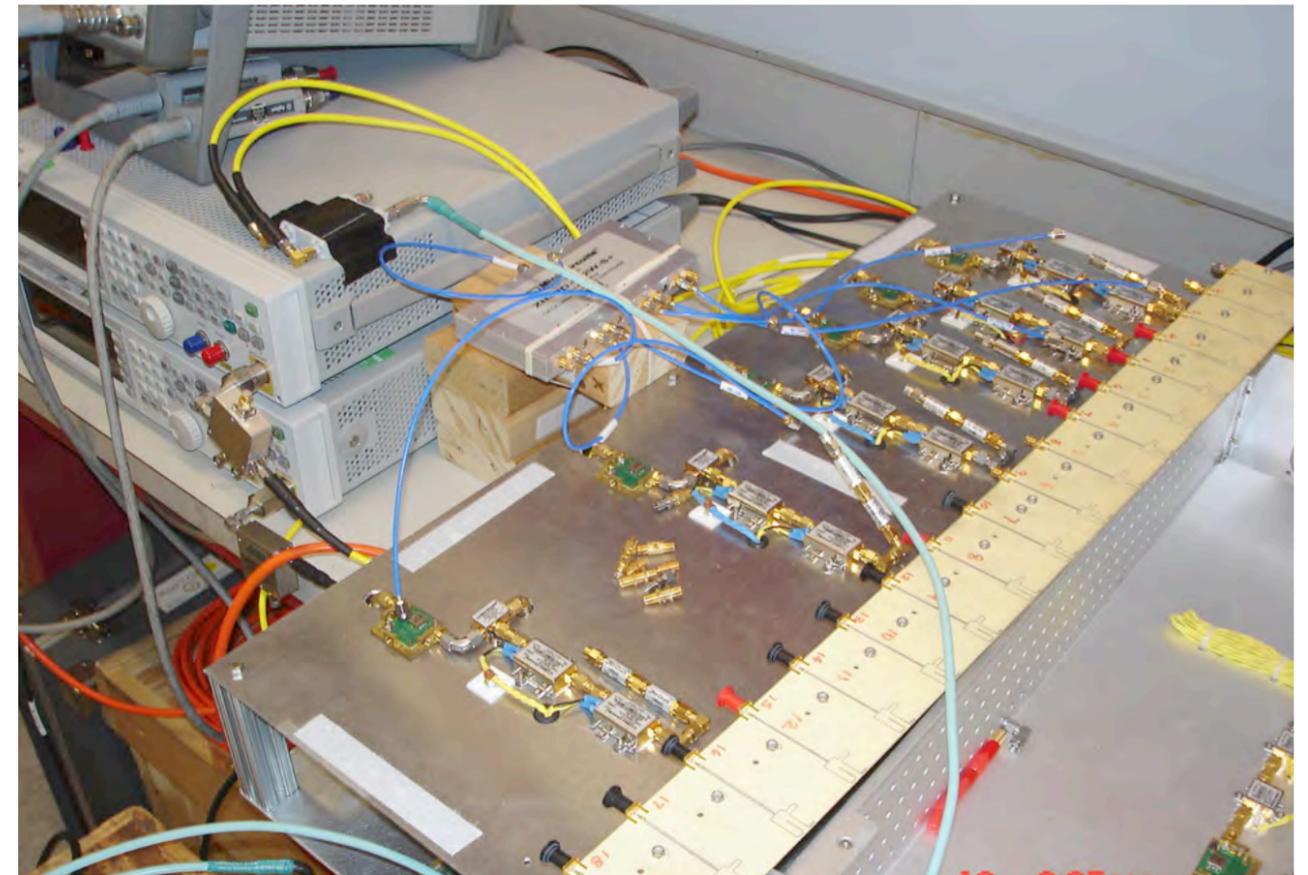


Figure 4: Array hardware shown to be configured as a six-element nested array.

would be a dramatic increase in the available degrees of freedom (DOF). DOF is the number of free variables in an equation that can be chosen without violating equation; the higher the number, the more flexibility there is in obtaining a desirable solution. The DOF for an array is dictated by the number of elements and imposes a limit on the number of sources that can be seen. For example, in the traditional linear model the number of physical sensors in the array  $N$  yields a total DOF of  $N-1$ , and is quite limiting for a sparse array with only a few elements. However, in the nonlinear model the number of DOF is given by the size of the virtual array, which has an upper limit of  $N(N-1)$ . By reducing the number of redundant spatial lags yielded by a sparse array we can get closer to the  $N(N-1)$  limit.

A major challenge of this effort is how to process the array data in order to fully exploit the theoretical gain in DOF discussed above, and to do so in a robust and speedy manner. Straightforward application of well-established signal processing methods used for ULAs faces a

number of theoretical and practical complications. Many approaches, such as the Multiple Signal Classification (MUSIC) approach,<sup>8</sup> rely on estimating a covariance matrix for the measured data. Traditionally this pertains to the physical sensor measurements of the ULA, but in the case of the virtual array the measurement covariance matrix is taken with respect to the covariance data of the sensors, which presumably means we need to estimate fourth-order statistics, since covariance data is itself a second-order statistic. This not only presents a number of mathematical difficulties (nonapplicability to Gaussian sources for example), but is likely to be far too impractical due to the long amounts of dwell time required. Rather than estimate 4th order statistics a recent study of ours considered techniques that do not explicitly require measurement covariance estimated.<sup>9</sup> As discussed in that paper a certain amount of dwell time is still needed to take enough snapshots to form usable virtual array data. Understanding the tradeoff space between established performance metrics and the number of snapshots is a major question that our effort will answer.

## Going from Simulations to Fielded Experiments

Currently there are a number of studies in the literature focusing on nonlinear processing for sparse arrays, but the majority of them have only demonstrated proofs of concept through computer simulations and often assume ideal signal models. While we are also developing new techniques based on simulated signal models, we also are in the process of validating these concepts experimentally.

A linear S-band (3.0–3.5 gigahertz) receive array that can support up to 18 elements half-wavelength spaced at 3.5 gigahertz will be used to conduct field experiments at the Naval Research Laboratory facility in Pomonkey, Maryland. At present the received signal at any six elements can be captured simultaneously, and we are in the process of upgrading this to 12. An initial field test was conducted last year at the Pomonkey facility, in which

a single transmitted plane wave source was used to get an initial characterization of a six-element nested array. This was done using a single fixed transmitter to excite the receiver array, which was mounted onto a tripod. The mounted array was then rotated in one-degree increments and sweeping an angular range from -60 to 60 degrees. The resulting pattern, as listed in Fig. 6, shows reasonable agreement between the measured and theoretical pattern.

Future experiments will arrange a variable number of sources in the far-field to emulate typical operating environments. By using arbitrary waveform generators to generate each source, we can model radar returns from targets and clutter, correlated returns such as multipath, and uncorrelated returns such as electromagnetic interference and noise jamming. These signals will be captured using ULA, nested, coprime, and MRA element arrangements.

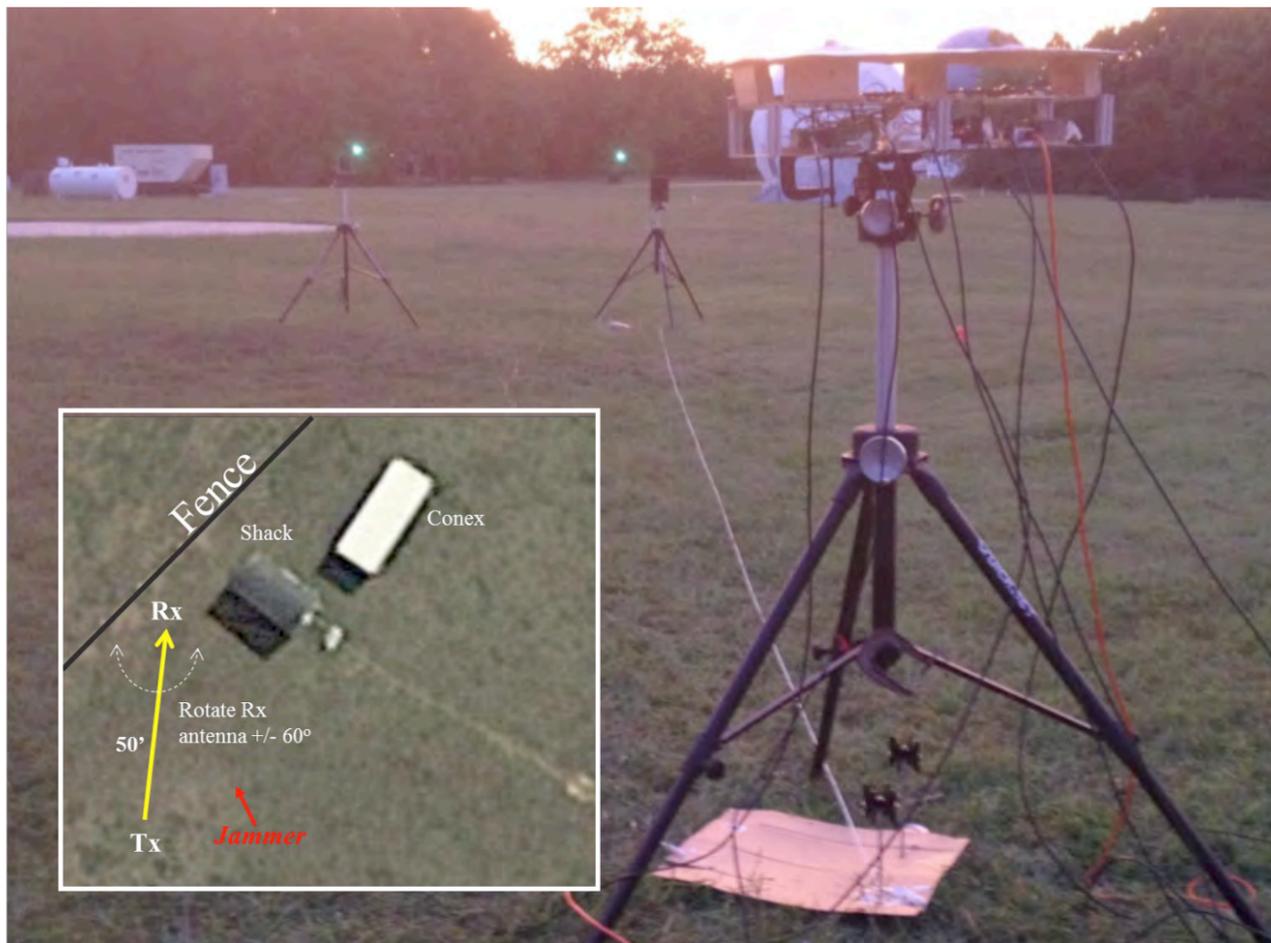


Figure 5: Characterizing the receiver array using a single transmit source.

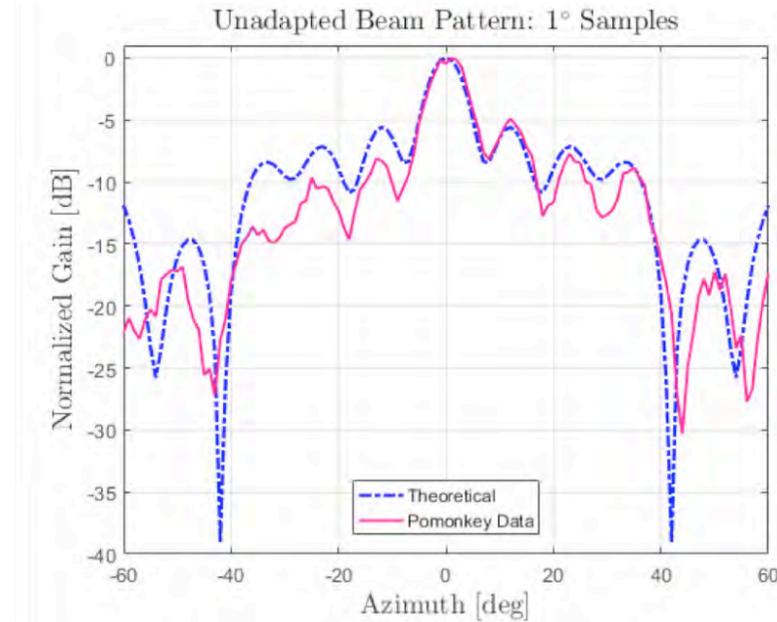


Figure 6: Initial data collection indicates a close match between the measured array pattern and a theoretical six-element nested array.

## Setting the Stage for Future Research

As the Navy trends towards lightweight, compact, and versatile autonomous platforms, research on sparse arrays will be crucial for maintaining our technological edge. It is the hope that the results of our basic research will set the stage for transitioning toward a more focused 6.2 effort. This will likely involve extension of the research onto arrays that conform to the surface of a particular platform and more general surface (2D) type of sparse arrays. Furthermore, while this 6.1 effort is radar-centric, the lessons learned here would be beneficial for other phenomenologies incorporating passive or active arrays, including sonar, radio astronomy, and underwater near-field electromagnetic applications.

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## About the authors:

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# A LOOK AHEAD

## The National Naval Responsibilities

▶▶

**F**or millennia, navies fought primarily on the sea. Today, navies and marine corps travel, fight, and surveil on, in, above, and below the sea, on land, and in space. This complex and challenging environment makes naval operations inherently difficult and dangerous even under the best conditions. The Department of Navy has historically placed great emphasis on maintaining a vigorous science and technology program in those areas where research is critically important to maintaining naval superiority.

Despite the greater variety of environments face by today's naval forces, the central enduring challenges of the world's oceans mean that many research areas are simply not addressed by investments from the other services, other government agencies, academia, or industry. This means that the health, strength, and growth of our scientific and technical capabilities in those fields depend upon the Department of the Navy.

To that end, the Office of Naval Research supports five research concentrations that are unique to the naval services and where the Navy historically has taken the lead, called the National Naval Responsibilities:

- Ocean acoustics—Understanding and accurately predicting the ocean operating environment provides an edge to US naval forces.
- Undersea weapons—The undersea domain demands capabilities with the highest reliability, precision, and safety possible.
- Naval engineering—The sea is unforgiving, presenting distinct engineering challenges to ship design, corrosion, maintenance, and platform affordability.
- Undersea medicine—Mitigating the effects of operating undersea enables greater freedom of action and optimized submariner and diver performance.
- Sea-based aviation—Operating aircraft at sea presents technical challenges exclusive to naval aviation in airframe structures, propulsion, avionics, and ship integration.

**The next issue of *Future Force* will explore these unique naval initiatives and their impact on the Navy.**



An F/A-18E Super Hornet with VFA-31 launches from the aircraft carrier USS *George H.W. Bush* (CVN 77). Because of the special rigors of operating aircraft at sea, sea-based aviation is one of the five unique National Naval Responsibilities that represent an important part of the Office of Naval Research's science and technology investment portfolio.

Photo by MC3 Matt Matlage



Dr. Sophoria Westmoreland, a support contractor with the Office of Naval Research, judges a poster session during the 55th National Junior Science & Humanities Symposium in San Diego, California. Supported by the Navy, Army, and Air Force, the symposium brings together 230 high school students who qualify for attendance by submitting and presenting original scientific research papers in regional symposia held at universities nationwide. (Photo by John F. Williams)

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