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April 2024

U.S. NAVAL RESEARCH LABORATORY

25 TECHNOLOGIES FOR THE NEXT 25 YEARS (2023–2048)

U.S. NAVAL RESEARCH LABORATORY
100
CENTENNIAL CELEBRATION 1923 - 2023

ON TO NRL's SECOND CENTURY OF DISCOVERY AND INNOVATION

U.S. Naval Research Laboratory taken from across the Potomac River by Jim Keikelejohn

NRL's Top 100 Science and Engineering Contributions (1923–2023)

- Permanent Magnet Materials
- Acoustic Matched-Field Processing
- Pulsed X-ray Radiography
- Gallium Nitride Transistor Development

AFFORDABILITY AND SUSTAINABILITY

- Gamma-Ray Radiography
- Principles of Fracture Mechanics
- Molecular Structure Analysis and the Nobel Prize
- Synthetic Lubricants
- Polytetrafluoroethylene for the Navy
- Quantitative X-Ray Fluorescence Analysis
- Improved Boilerwater Treatment
- Fracture Test Technology
- Semi-Insulating Gallium Arsenide Crystals
- Ion-Implantation Metallurgy
- Fluorinated Network Polymers
- Magnetic Materials and Semiconductor Technology
- Low-Solar-Absorbance Ship Paint
- Rapid-Cure Corrosion-Control Coatings
- Topside Camouflage and Nonskid Deck Coatings
- High-Temperature Nonskid Decking

SPACE RESEARCH AND TECHNOLOGIES

- First Far-Ultraviolet Spectrum of the Sun
- First Detection of X-Rays from the Sun
- Viking Sounding Rocket Program
- Vanguard Program — The Rocket
- Vanguard Program — Minitrack and Space Surveillance
- Vanguard Program — Satellites and the Science
- X-Ray Astronomy
- Solar Radiation (SOLRAD) I
- America's First Operational Intelligence Satellite
- TIMATION and NAVSTAR GPS
- Remote Sensing of the Upper Atmosphere
- Spaceborne Solar Coronagraphs
- Maritime Domain Awareness
- Deep Space Program Science Experiment (Clementine)
- Interferometry at Optical Wavelengths
- Tactical Satellites

AUTONOMOUS SYSTEMS

- Dragon Eye
- Hydrogen Fuel Cells for Unmanned Systems

DIRECTED ENERGY

- High-Power, High-Current, Pulsed-Power Generators
- Excimer Laser Technology
- First Operational Shipboard Laser Weapon

PERSONNEL PROTECTION

- Improved Aircraft Canopy and Window Materials
- Purple-K-Powder
- Radiation Detection
- Nuclear Reactor Safety
- Marine Surface Monolayers
- Optical Immunoassays and Sensors
- Surface Acoustic Wave Chemical Sensors
- CT-Analyst®
- Project Silent Guardian
- Personal Protective Equipment and Injury Biomechanics
- Transparent Armor

U.S. NAVAL RESEARCH LABORATORY
25 Technologies for the Next 25 Years (2023–2048)

NRL's Top 100 Science and Engineering Contributions (1923–2023)

This list is only representative of thousands of unclassified accomplishments, many of them still classified, that NRL has produced since opening its gates on July 2, 1923. It should be noted that the more recent achievements may not have yet reached full fruition in terms of applications and impact. Even so, the 100 accomplishments confirm that NRL exerts a broad and powerful influence on our Navy and our republic through the work of dedicated government scientists, engineers, and support personnel who serve the nation's interests.

These achievements exemplify the Laboratory's extraordinary impact on American sea power and national security. Many of its contributions were made during times of great peril to our nation, the free world, and demoncracy. NRL has changed the way the U.S. military fights, improved its capabilities, prevented technological surprise, transferred vital technology to industry, and tilted the world's balance of power on at least three occeasions with the first U.S. radar, the world's first intelligence satellite, and the first operational satellite of the Global Positioning System.

NRL has helped create — in league with its government, university, and industry partners — the most formidable naval fighting force on earth, which, in turn, shaped America's role in the world. Reflection on our accomplishments encourages and prepares us for the exertions and sacrifices required to meet tomorrow's inevitable challenges.

ELECTROMAGNETIC WARFARE
- Invention of U.S. Radar
- Plan-Position Indicator
- Identification Friend-or-Foe Systems
- Monopulse Radar
- First American Airborne Radar
- Radar Absorbing Materials and Anechoic Chambers
- Over-the-Horizon Radar
- High-Resolution Radar
- High-Frequency Direction Finding
- Super Rapid-Blooming Offboard Chaff
- Specific Emitter Identification
- Inverse Synthetic Aperture Radar
- Infrared Threat Warning
- AN/ALE-50 Towed Countermeasures
- Anti-Ship Missile Defense Radar
- NULKA Offboard Countermeasure System

UNDERSEA WARFARE
- First Operational Fathometer
- First Operational U.S. Sonar
- First Proposal of a Nuclear Submarine
- Deep Ocean Search
- Submarine Habitability
- Fiber-Optic Interferometric Acoustic Sensors
- Generalized Nearfield Acoustical Holography
- Fixed-Wing Airborne Gravimetry
- Structural Acoustics

COMMUNICATIONS, INFORMATION TECHNOLOGY, AND CYBER WARFARE
- Development of High-Frequency Radio Equipment
- Radio Propagation and the "Skip-Distance" Effect
- Aircraft Radio Homing System
- First Operational Satellite Communication System
- Secure Voice Communication
- Key Distribution & Management for Cryptographic Equipment
- Tactical Communications
- Free-Space Optics Communications
- Flying Squirrel
- Onion Routing and Tor

BATTLESPACE ENVIRONMENTS
- Wind-Speed Measurement Using Microwave Imaging
- Optical Fiber Gyroscope
- NOGAPS / NAVGEM Global Weather Prediction
- Decadal Impact of El Niño
- Mesoscale Prediction Systems
- Mountain Wave Forecast
- Hyperspectral Imager for Tactical and Environmental Uses
- Global Ocean Forecast System
- Regional Tropical Cyclone Prediction Systems
- WindSat Spaceborne Polarmetric Microwave Radiometer

ENABLING SCIENCE AND TECHNOLOGY
- Liquid Thermal Diffusion Process
- High-Power Neodymium Glass Lasers
- `Flux-Corrected Transport

Foreward

The Naval Research Laboratory (NRL) was inaugurated on July 2, 1923. Since that time, it has helped build — in league with its government, university, and industry partners — the most formidable naval fighting force on earth, which in turn helped to enhance America's security, prosperity, and role in the world. NRL's centennial invites us to reflect on an extraordinary record of sustained achievement. But the very nature of both science, innovation and our mission compel us to move forward and look into the unknown, not back at the familiar. Tomorrow's challenges will not wait for us to act.

Naval superiority is essential to deterrence and freedom of the seas. And when called upon to go into harm's way, the U.S. Navy and Marine Corps must be equipped with the weapons and capabilities to fight and win. This publication features 25 science and engineering concepts under development that may play an important role in meeting national security needs over the next 25 years. However, these select narratives are only representative of many NRL projects, both unclassified and classified, framing future options. They offer the potential to yield powerful new capabilities for our Navy and republic.

Dr. Bruce G. Danly
Director of Research
U.S. Naval Research Laboratory

March 2024

25 Technologies for the Next 25 Years

(Listed by Mission Area)

Seeing Explosives, Chemicals, and Pathogens Around Us

25

Explosives, narcotics, toxins, pathogens, and chemical or biological warfare agents can be difficult and dangerous to detect with traditional methods such as swipe sampling from surfaces. Optical approaches can provide a non-contact standoff detection capability that utilize the unique chemical signatures of the threat substance. NRL has pioneered Infrared Backscatter Imaging Spectroscopy (IBIS) for non-contact standoff detection. IBIS incorporates compact, eye-safe, invisible, and stealthy infrared quantum cascade lasers (QCL's) to interrogate surfaces while collecting the backscattered signal using an infrared camera. IBIS technology can successfully locate and identify a range of trace threat chemicals and the technology is being advanced for operational and security environments.

POC: Dr. Chris Kendziora – chris.a.kendziora.civ@us.navy.mil

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25 Technologies for the Next 25 Years (2023–2048)

PERSONNEL PROTECTION

Deployable DNA Sequencing for Naval and Expeditionary Operations

24

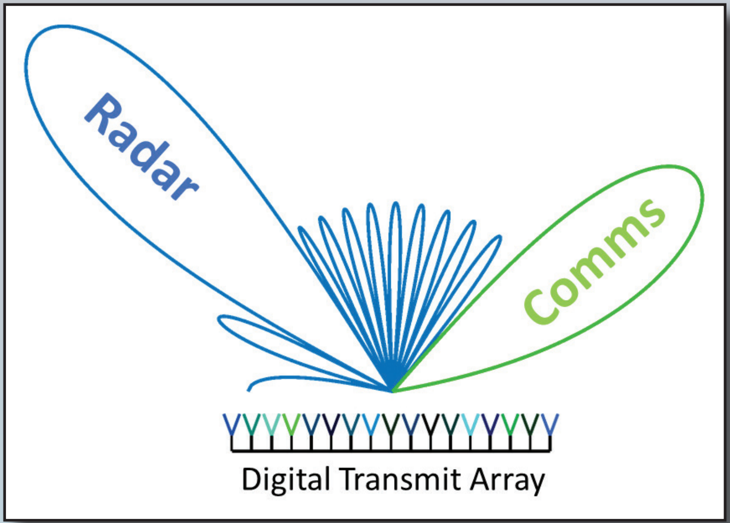
DNA sequencing – the ability to "read" DNA – is considered the gold standard method for identifying organisms and determining their biological potential. While recognized as a critical capability for the Department of Defense, current sequencing workflows are not suited for the light, mobile, and expeditionary nature of naval operations. Process development and improvements are needed to provide actionable information in near-real time at the point of need. As a recognized leader in fieldable DNA sequencing, NRL and its expeditionary platform partners will continue to lead in the development of customized sequencing capabilities for emerging Navy-specific concept of operations and requirements.

POC: Dr. Gaurav Vora – gaurav.j.vora.civ@us.navy.mil

ELECTROMAGNETIC WARFARE

Radar Arrays for Communication

1



The evolution of Navy radar from analog phased arrays to increasingly digital architectures has enabled multiple simultaneous beams on receive, while transmit remains largely limited to a single function at a time. This asymmetry is increasing untenable, as radars evolve into distributed systems reliant on robust communications links often provided by the radars themselves. The key obstacle is the saturated amplifiers used on transmit, as their nonlinearity precludes conventional linear beamforming. NRL is currently conducting fundamental research into array-waveform designs which are compatible with existing and future radar transmitters, setting the stage for future applied research.

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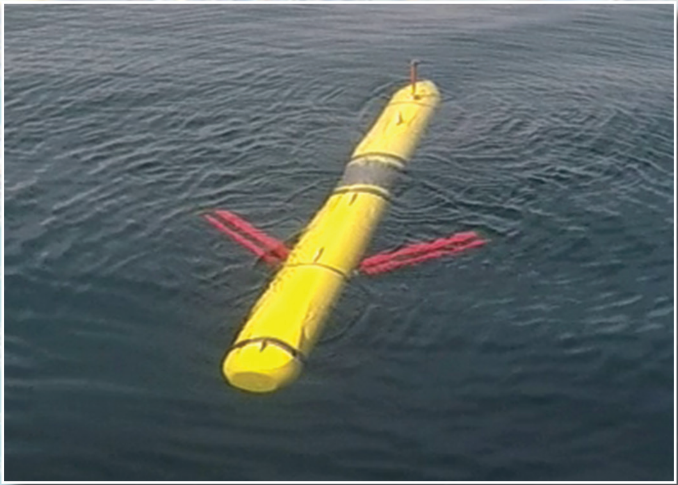
25 Technologies for the Next 25 Years (2023–2048)

Coordinated Autonomous Underwater Multi-Vehicle Sonars Operations

2



Marrying the recent NRL breakthroughs on AUV-based structural acoustic sonar technology exploiting acoustic color fingerprints to the expected future advances in underwater system autonomy, artificial-intelligence technology, compact energy sources, and underwater acoustic communications will enable long duration unmanned, coordinated underwater sonar operations with multiple AUVs. Such unmanned and non-operator controlled fleets will provide the Navy with significantly increased sonar capabilities in littoral anti-submarine warfare, mine countermeasure operations, and counter UUV missions. Such a capability will also support affordable comprehensive diagnostic exercises to characterize and reduce the acoustic vulnerability of the Navy's own underwater assets.

POC: Dr. Peter Herdic– peter.c.herdic.civ@us.navy.mil

Pulsed Lasers as Next-Generation Directed Energy Weapons

23

Pulsed lasers, with their ultra-high-intensity beams, have the potential to revolutionize defense of Navy vessels against missiles, small boats, unmanned aerial vehicles, and emerging threats by enabling new, scalable, lethality mechanisms not available from conventional lasers. Science and technology advances in laser technology, beam control, and knowledge of how materials and systems respond to high-intensity laser pulses are needed to realize such a vision. NRL is at the forefront, developing the models and facilities needed to enable laser systems that should transform how we employ warships, support forces ashore, and deliver power projection to meet modern security challenges.

POC: Dr. Michael Helle – michael.h.helle.civ@us.navy.mil

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25 Technologies for the Next 25 Years (2023–2048)

AUTONOMOUS SYSTEMS

Collaborative Operations for Uncrewed Aerial Systems

22

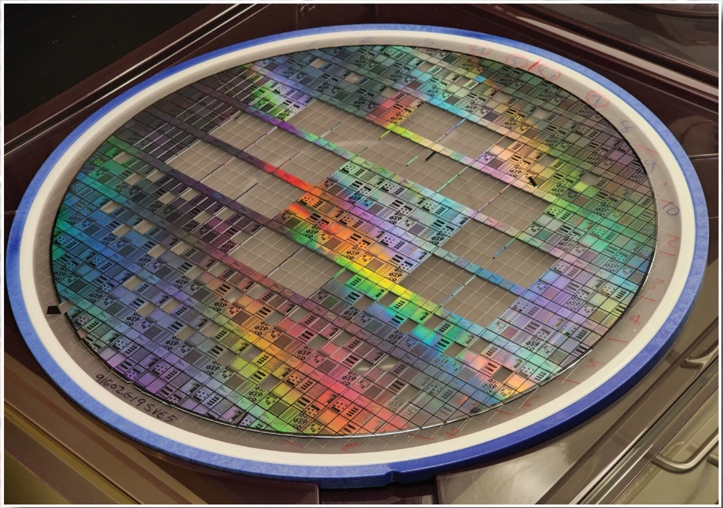
Collaborative autonomous operations for uncrewed aerial systems (UAS) has the promise to bring the warfighter capability to overwhelm adversarial assets with low-cost assets and conduct mission operations in areas where access to human control and datalinks are denied. NRL has been a leader in conducting flight experiments and demonstrations of collaborative, uncrewed systems in operationally relevant environments. By continuing to conduct research in novel autonomy algorithms, sensors, payloads, and hardware for processing data at the edge, collaborative autonomous systems are on the cusp of being a deployed reality and revolutionizing tactical warfighting operations.

POC: Dr. Thomas Walls – thomas.j.walls24.civ@us.navy.mil

COMMUNICATIONS, INFORMATION TECHNOLOGY, AND CYBER WARFARE

Silicon Photonics — The Next Integrated Circuit Revolution

3



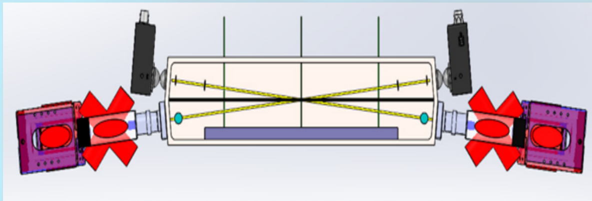
Silicon photonics is bringing light directly onto the semiconductor chips that power our computers and defense technologies. These photonic integrated circuits are poised to revolutionize computing as well as DoD-specific applications such as quantum sensing, biological and chemical analysis, and high-frequency radar signal processing. Introducing new photonic materials to microelectronics processing and developing improved photonics packaging remain key hurdles for silicon photonics. Through leadership in the DoD-sponsored domestic state-of-the-art foundry at AIM Photonics Institute, NRL and its DoD partners have led and will continue to lead the development of photonic integrated circuits targeted specifically to DoD applications.

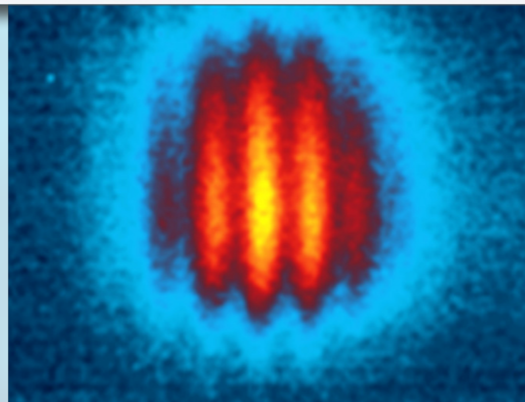
POC: Dr. Peter Goetz – peter.g.goetz.civ@us.navy.mil

COMMUNICATIONS, INFORMATION TECHNOLOGY, AND CYBER WARFARE

Quantum Sensors for Positioning, Navigation, and Timing

4





The Naval Research Laboratory is creating new sensor architectures for measurement of acceleration, rotation, gravity, and magnetic fields to enable long periods of GPS-free navigation. Current work in atomic physics, quantum optics and material synthesis is producing fundamental understanding of laser cooled atoms and semiconductor color centers. This builds a foundation for the design and fabrication of sensor architectures operating on principles of quantum superposition and entanglement. Maturing these sensors technologies will enable advanced Naval timing, communications, navigation, surveillance, and reconnaissance capabilities.

POC: Dr. Allan Bracker – allan.s.bracker.civ@us.navy.mil

AUTONOMOUS SYSTEMS

Infinite Endurance Unmanned Air Systems

21

The Naval Research Laboratory is developing the technologies and strategies that allow small unmanned vehicles to sustain flight at net zero energy. Achieving this goal requires advances on all fronts — energy collection, conversion, and storage, efficient aerodynamics and path planning, materials and structural performance, and enabling autonomies. These advances will open opportunities for new systems launched farther from operational areas while requiring fewer resources to sustain them. The resulting missions will realize greatly increased utility, impact in effectiveness and value to the warfighter.

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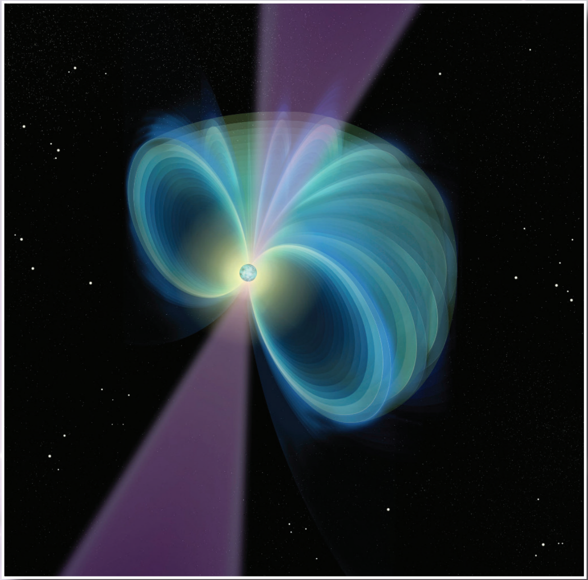
25 Technologies for the Next 25 Years (2023–2048)

Navigation in Space Using X-ray Pulsars

20



Pulsars are spinning neutron stars that are nature's most stable clocks. An X-ray sensor on a spacecraft can observe their pulses and autonomously determine its location and velocity. NRL, working with NASA, has developed this technology and performed the first in-orbit demonstration. NRL is proceeding to shrink and improve the sensor technology and to find and characterize more of these natural clocks. This can provide resilience to GPS outages and allow missions to autonomously navigate in cislunar and interplanetary space.

POC: Dr. Paul Ray – paul.s.ray3.civ@us.navy.mil

Neuromorphic Processing — Fast, Low Power, Edge Computing Systems

5

Neuromorphic processing is an approach to building computers that work the way the brain does. Neuromorphic processors use many independent silicon "neurons" that talk to each other through voltage spikes. Each neuron operates immediately (and only) when it receives enough spikes from its neighbors. This makes neuromorphic processors both fast and energy efficient. However, it also makes them "non–differentiable," which means they cannot be trained the way more standard artificial neural networks are. NRL is developing novel chip designs and ways of training spiking neural networks that are inspired by traditional theories of how learning occurs in the brain.

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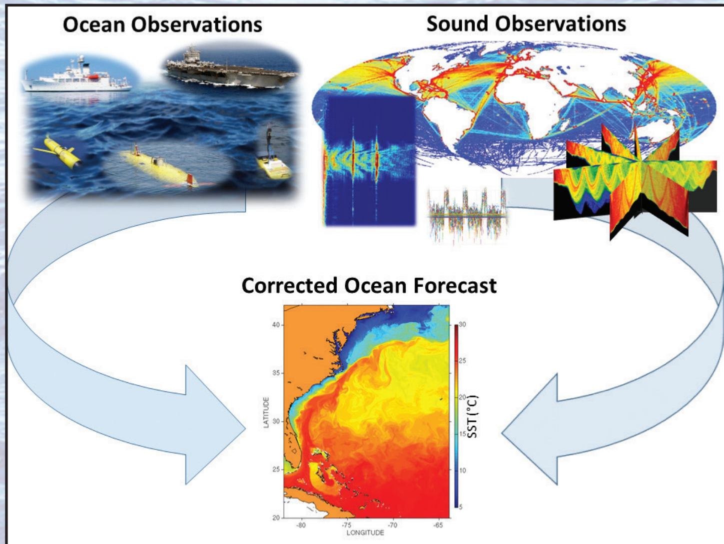
Using Sound to Make Accurate Ocean Forecasts

6

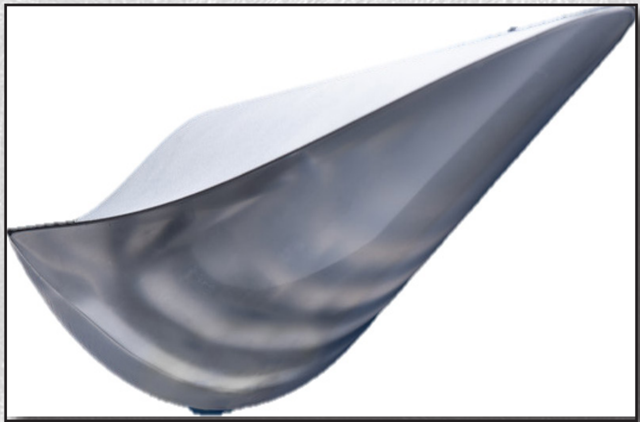


Underwater sound energy can be used to sense the ocean environment (temperature and salinity) and update and correct the Navy operational ocean forecast models. This is done by integrating software that translates ocean sound to temperature and salinity (and vice versa). These observations are not point-wise; rather, they provide ocean environmental information along the entire path from sound source to receiver. This has the potential to provide far more information in order to correct the ocean forecast than any single profiling float or expendable bathythermograph.

POC: Dr. Matthew Carrier – matthew.j.carrier6.civ@us.navy.mil

Hypersonic Systems for Defense and Space Access

19

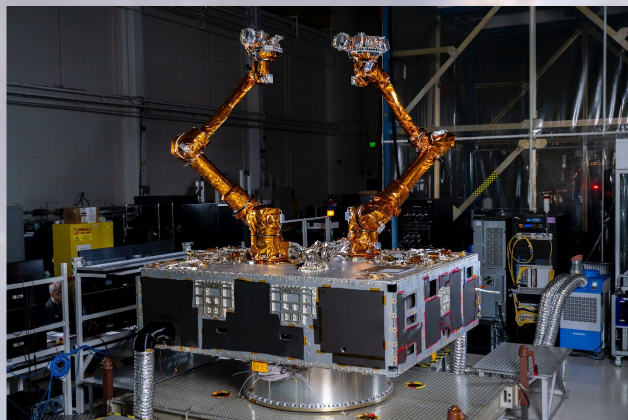


In our modern era of guided missile warfare, speed and maneuverability will be key in determining the outcome of engagements with sophisticated adversaries. Cost and quantity are additional critical metrics for approaching or deterring such conflict, implying the necessity of proliferated tactical hypersonic systems that provide game-changing performance with minimal systems engineering design margins. As aircraft and rocketry have shown historically, hypersonic aerodynamic, propulsion, controls, and materials technologies developed for strike and defense will have dual-use applications for 5-20x faster civil air transport and space access vehicles for launch, re-entry, and inter-planetary missions.

POC: Dr. Jesse Maxwell – jesse.r.maxwell3.civ@us.navy.mil

Robotic Servicing of Satellites

18

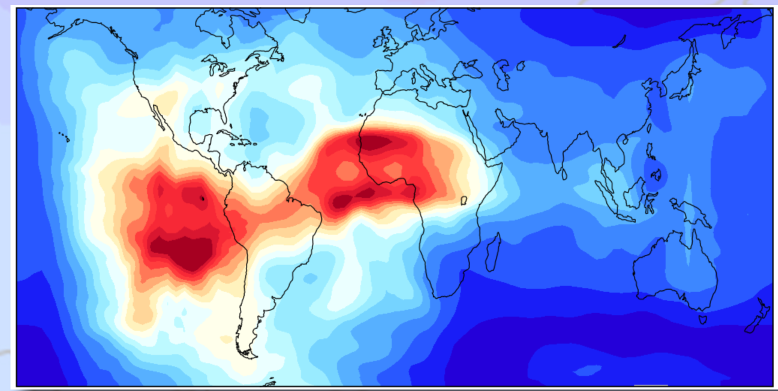


Satellites perform critical national defense, science, and commerce missions – but unlike airplanes or ships or tanks, a satellite can't be fixed when it breaks or upgraded when its sensors are out of date. NRL has spent over two decades designing and building robotic spacecraft that can safely and reliably repair and upgrade billion dollar commercial and DoD satellites. In the near future, robotic satellite "mechanics" will be able to extend the useful life of satellites, upgrading their flight computers, batteries, and sensors. And we are working on robots that will someday build massive telescopes or solar power stations in orbit.

POC: Mr. Bernard Kelm – bernard.e.kelm.civ@us.navy.mil

Whole Atmosphere Prediction — Connecting Terrestrial and Space Weather

7

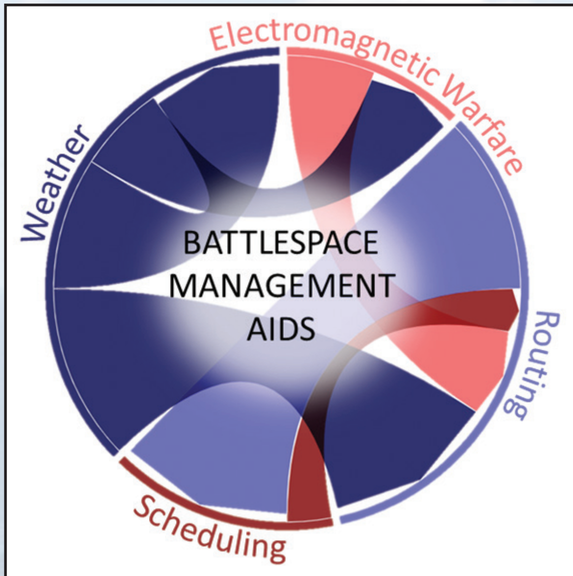


The Navy battlespace encompasses ocean, atmosphere, and space, yet no operational naval capability exists to forecast space-weather affecting the globally deployed Fleet. The challenge is both computational and scientific, requiring a new generation of coupled whole atmosphere forecast models driven by the ocean from below, by the Sun from above, and mutually interacting with ionospheric and magnetospheric models above 100 km altitude. Multidisciplinary NRL researchers and outside partners will continue to define new pathways making future integrated atmospheric and space weather prediction a reality.

POC: Dr. Stephen Eckermann – stephen.eckermann.civ@us.navy.mil

Meta-optimization for Navy Battlespace Management

8

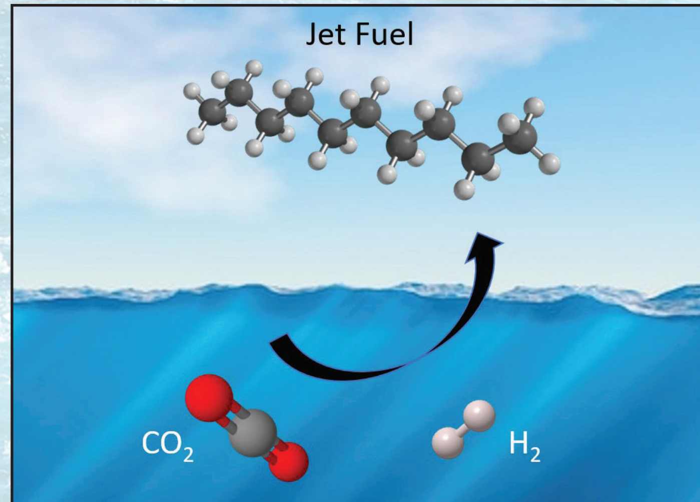


With the proliferation of independent Navy battle management aid (BMA) procurement, there are a multitude of optimization schedulers, planners, managers, etc., at the disposal of operational planners. In a multi-domain, multi-mission conflict, independently optimized decision guidance across independent BMAs will provide, at best, inconsistent guidance. Meta-optimization is new research that attends to this widening gap in multi-BMA interaction management for distributed maritime operations (DMO), contested environments, etc. Meta-optimization is an overarching information sharing network that can relieve workloads across BMAs, while siphoning pertinent, relevant, and timely information to the "right" BMAs to increase performance, fidelity, and flexibility of decision guidance.

POC: Dr. David Sidoti – david.m.sidoti.civ@us.navy.mil

Operational Fuel from Seawater

17



NRL has developed scalable modular technologies to produce operational fuel from seawater using carbon dioxide (CO_2) and hydrogen (H_2). NRL's E-CEM* process extracts CO_2 and produces H_2 from seawater. These gases are combined in an NRL catalytic gas-to-liquid process to produce military grade fuel where and when needed. These modular technologies are scalable and will produce useable fuel that meets military specification in remote areas of operation (littoral or at sea). The ability to generate fuel at the point of use provides the U.S. Navy with energy security and independence and a reduced logistics footprint, providing the freedom of action required for its mission.

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AFFORDABILITY AND SUSTAINABILITY

Biomanufacturing — Securing DoD Supply Chains

16

Biomanufacturing represents a paradigm shift in chemical manufacturing using microorganisms as programmable living biofoundaries capable of on-demand production of critical molecules. This capability is poised to impart unprecedented control over the molecules that we can make domestically to secure the U.S. supply chains, both domestic and point-of-need, from foreign instabilities. NRL is developing new tools to expand the pool of biomanufacturing-ready microorganisms and novel bio-optimized production processes, key challenges to unlocking the full potential of biomanufacturing. Through strategic partnerships with DoD and industry, NRL has placed itself as a leader for the Navy and Marine Corps in the biomanufacturing space.

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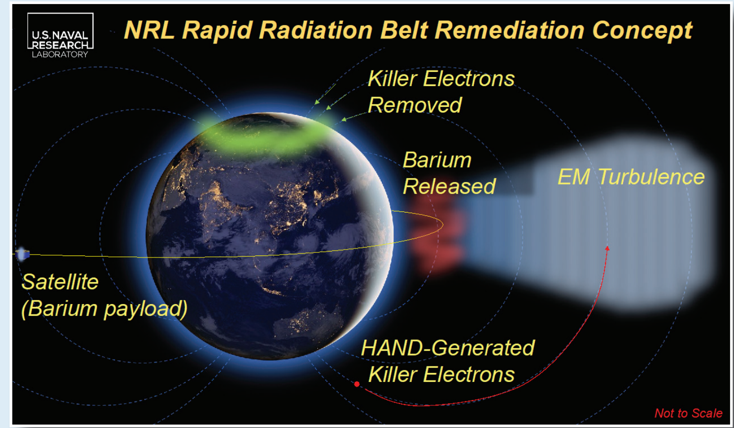
BATTLESPACE ENVIRONMENTS

Rapid Radiation Belt Remediation System

9

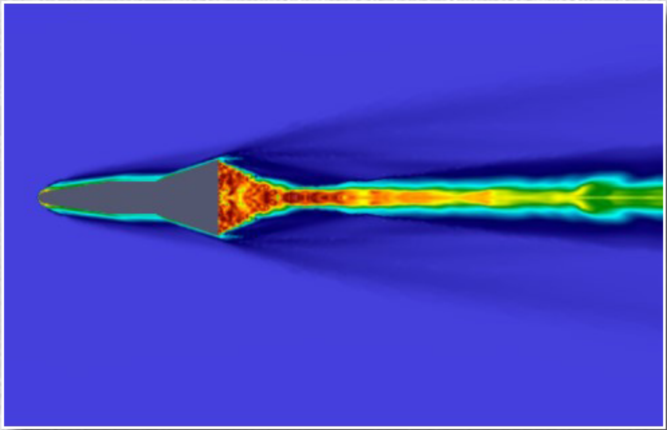


A High Altitude Nuclear Detonation (HAND) generates 'killer' electrons that are trapped by the earth's magnetic field for years and can cripple naval operations by degrading or destroying Navy/DoD space-based sensors. NRL has developed a Rapid Radiation Belt Remediation (RRBR) technique to rapidly precipitate these "killer" electrons. The key physics of RRBR has been validated in laboratory experiments. A full-scale space demonstration of the concept is planned, to be followed by the design of a prototype for an operational HAND countermeasure that will protect critical Navy/DoD space-based sensors from severe radiation damage and assure seamless information flow to our warfighters.

POC: Dr. Gurudas Ganguli – gurudas.i.ganguli.civ@us.navy.mil

Physics-Informed Machine Learning: Enabling Next-Generation Multiphysics Simulations

10



Many critical Navy applications, from ocean modeling to detailed hypersonics calculations, produce intractable simulation challenges unless simplified in complexity or scale. Physics-informed machine learning is providing an approach to overcome this bottleneck. By integrating physics-based constraints, such as traditional conservation laws, powerful machine learning techniques can capture complicated, nonlinear relationships within data. With physics informed machine learning we can create accurate models from less data, integrate data-driven models into larger physics-based simulations more effectively, and provide verification that the results are trustworthy. These techniques should help to accelerate a new generation of physics-based computational simulations.

POC: Mr. Adam Moses – adam.j.moses.civ@us.navy.mil

Shipboard Maintenance Using Low Power Neuromorphic Computing

15

Power and energy are ubiquitous and vital concerns to the Department of Defense. A method of greatly reducing the power requirements for autonomous systems, artificial intelligence, and robots will provide a military advantage. Neuromorphic computing is an emerging technology that could help solve these fundamental power concerns. Current robot neuromorphic systems can perceive tools, perform simple cleaning, and handoff tools to humans. NRL's quadruped robots currently perform these shipboard maintenance tasks at NRL's Laboratory for Autonomous Systems Research in a ship mockup; further research will expand to additional shipboard capabilities, such as perception and anticipation, and underwater mapping and communication.

POC: Dr. Greg Trafton – greg.j.trafton.civ@us.navy.mil

Microwave Power Beaming

14

Microwave power beaming is the efficient point-to-point transfer of electrical energy across free space by a directive microwave beam. U.S. forces and remote installations are currently powered by fuel transported at great expense to difficult-to-reach locations. At times of conflict, delivering this fuel exposes U.S. forces to continuous jeopardy over great distances, resulting in the diversion of significant intelligence, surveillance, reconnaissance, and defensive resources to prevent casualties. Microwave power beaming can deliver this power instantaneously, without interruption, and without risk of human life. Extending microwave power beaming to space-to-earth applications and to unmanned platforms with severe size, weight, and power constraints would provide additional options for operational energy.

POC: Dr. Christopher Rodenbeck
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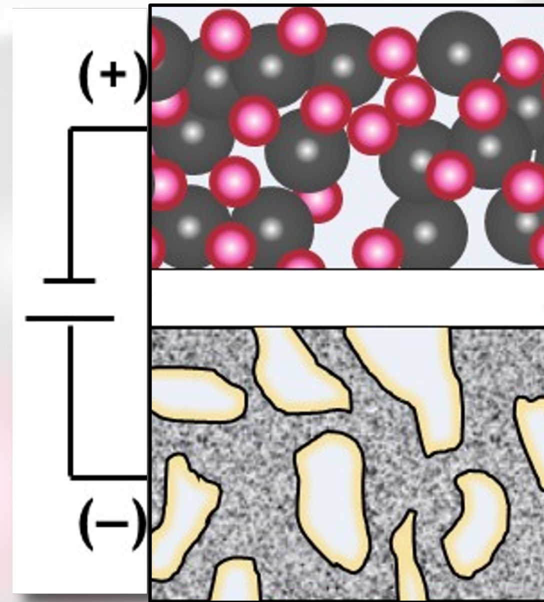
Next-Generation Batteries with Mission-Enabling Capability, Safety, and Sustainability

11

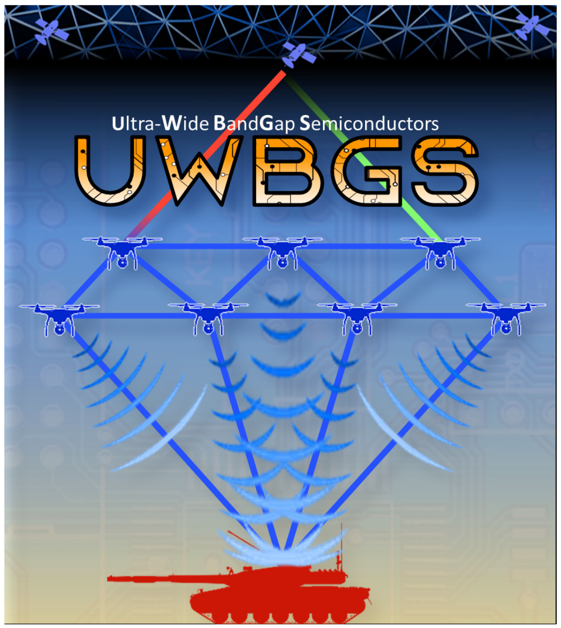


For the Department of Defense, "No Power = No Mission" since all military missions require reliable power sources that are safe to transport, store, and operate under mission conditions. While lithium-based batteries now dominate the energy-storage landscape, their persistent safety concerns have led NRL scientists to develop high-performance, safe, and low-cost battery alternatives. Recently, NRL developed a zinc "sponge" anode. With interpenetrating networks of metallic scaffolding and voids, electrochemical and chemical reactions are distributed into the sponge interior, eliminating the long-standing dendrite formation problem. Now, aqueous-based zinc battery chemistry is an enabling robust, safe, and energy-dense battery replacement for lithium-ion batteries.

POC: Dr. Debra Rolison – debra.r.rolison.civ@us.navy.mil

Ultrawide Bandgap Semiconductors for Next Generation Radio Frequency and Power Microelectronics

12



NRL is leading the defense community in the research and development of an emerging class of electronic materials, known as ultrawide bandgap semiconductors. These materials have an intrinsic ability to operate at higher voltage and power density than conventional semiconductors used today. Materials such as diamond, cubic boron nitride, aluminum nitride, and gallium oxide will lead to revolutionary performance advancements in high speed transistors. This technology will extend highly-efficient solid-state power amplifiers and power conversion capabilities to size, weight, and power-constrained platforms, furthering Department of Defense electromagnetic spectrum dominance.

POC: Dr. David Meyer – david.j.meyer90.civ@us.navy.mil

ENABLING SCIENCE AND TECHNOLOGY

Quantum Computing — Processing Information in the Quantum World

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Information processing is ubiquitous and vital to the Department of Defense, and any edge in computing capability provides a military advantage. Quantum computing is an emerging technology that could help solve our most challenging numerical problems. The fundamental unit in quantum computing is the qubit, the state of which can be the classical bit state 0 or 1, or any linear combination — superposition — of the two. Combining qubits into a register allows a quantum computer to process superpositions of exponentially many classical states that on a classical computer would require an unfeasible amount of time and resources.

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