Marine Corps cryptologic analyst assigned to 1st Radio Battalion, I Marine Expeditionary Force Information Group, monitors electromagnetic spectrum during training in support of Command Post Exercise at Marine Corps Base Camp Pendleton, California, December 12, 2018 (U.S. Marine Corps/Brendan Mullin)

Unmasking the Spectrum with Artificial Intelligence

By Matthew J. Florenzen, Kurt M. Shulkitas, and Kyle P. Bair

Imagine you are a combatant commander (CCDR) equipped with the latest capabilities today's military has to offer. Your troops are armed with fifth-generation aircraft, precision-strike capabilities, advanced naval forces, and fully networked combat arms and land forces. From your command center you can precisely observe your forces on the battlefield, and your surveillance equipment allows unmitigated access to their actions and communications in real time. However, when you take this state-of-the-art force into combat against a near-peer competitor, nothing seems to work. Communications are at best intermittent and at worst nonexistent, your modern aircraft and naval assets cannot integrate operations, and your combat arms are relegated to utilizing line-of-sight communications to control the battle. The Clausewitzian "fog of war" settles on the joint operation, inducing confusion, ambiguity, and missed opportunities to advance the mission. At the tactical and operational levels of war, the ability to pass real-time decisions is gone, and the latency of information delays command decisions for 24 to 72 hours. The

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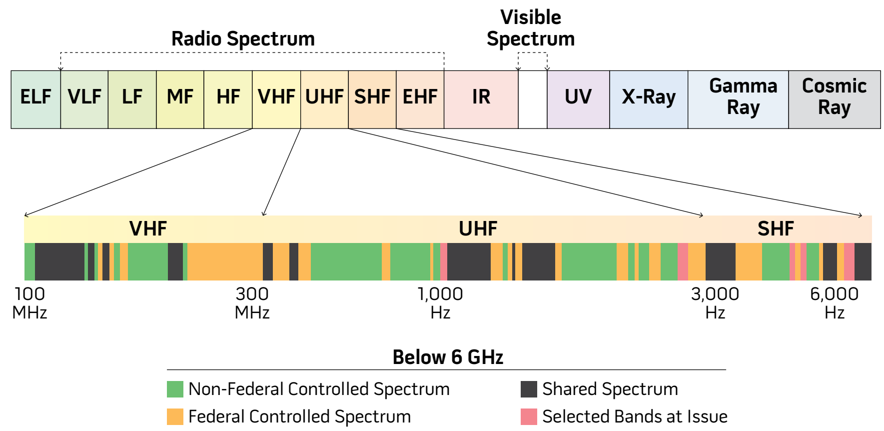
combined arms firepower of your joint force—the cornerstone of U.S. military doctrine—is combat-ineffective.

In this scenario, one potential issue complicating your operations might be an enemy exploiting your force's reliance on the electromagnetic spectrum (EMS). What do you see when you envision the EMS? It could be nothing that comes to mind, or maybe you picture the static joint doctrine description shown in figure 1. This article examines the benefits and risks associated with integrating artificial intelligence (AI) and machine learning (ML) technologies into the command and control (C2) systems guiding joint electromagnetic spectrum operations (JEMSO). To scope this discussion, this article examines how AI and ML solutions can improve a CCDR's ability to visualize, comprehend, and make informed decisions regarding the electromagnetic operating environment (EMOE).[1]

Figure 2 portrays how the U.S. Army perceives the EMOE. In today's information age, speed in the battlespace is predicated on information and the joint force's overall understanding of how the EMOE functions in joint operations. Understanding and visualizing the EMOE are crucial as military and civilian network interconnectedness and reliance on reliable access to the EMS increases. In turn, this interconnectedness and reliance help clarify the root problem: spectrum operations in today's information age and against a near-peer competitor pose significant regional and global challenges that will ultimately complicate a CCDR's ability to visualize and understand the EMOE with the required fidelity to make timely and appropriate JEMSO decisions. With this problem identified, this article examines the following question: can AI and ML improve a CCDR's understanding of a contested EMS, and what potential data quantity and quality pitfalls must be understood?

Three lines of effort are used to dissect this complex question. First, the article builds a common understanding of why AI and ML are being considered to improve CCDR EMS visualization. Second, it examines the potential roles

Figure 1. The Electromagnetic Spectrum



The top bar shows how the electromagnetic spectrum is divided into various regions and indicates that portion referred to as the radio spectrum. The lower bar illustrates the division of Federal, non-Federal, and shared bands for a critical part of the radio spectrum.

Legend

EHF: extremely high frequency
ELF: extremely low frequency
GHz: gigahertz
HF: high frequency
IR: infrared
LF: low frequency
MF: medium frequency
MHz: megahertz
SHF: super-high frequency
UHF: ultrahigh frequency
UV: ultraviolet
VHF: very high frequency
VLF: very low frequency

for AI- and ML-enabled EMS visualization systems and provides a sample of what is currently available. Finally, it addresses the potential impacts of data types regarding AI and ML integration that must be considered in order to minimize risk. With this understanding of where we are currently, the capability of AI/ML to improve our EMS visualization and understanding, and clear appreciation for the role of data inputs to these systems, we gain a better appreciation of AI- and ML-enabled EMS visualization systems and how they might improve the decision cycle within the EMOE.

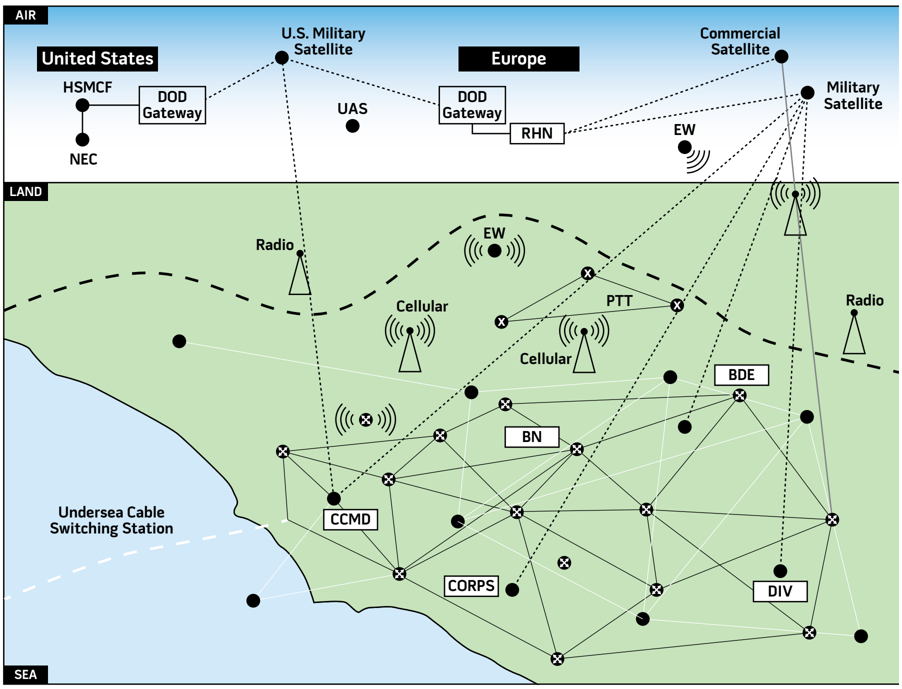
Impetus

Most of our modern military (and civilian) capabilities, warfighting systems, and businesses depend on open, trusted, and constant use of the EMS. Policies and procedures must lay the foundation for planning and mission preparation in a complex electromagnetic environment. The National Security Strategy, National Intelligence Strategy, and joint doctrine generally agree that near-peer competitors to Western ideals recognize the significant advantages provided by effective EMS operations. These important documents clearly indicate that developing and resourcing an electromagnetic capability to deter and defeat threats are imperative to U.S. national interests.

Ensuring constant and reliable access requires significant EMS connections to facilitate modern command, control, and communication linkages across military systems. The joint force attempts to achieve a credible means to maneuver within the EMS through joint electromagnetic spectrum management operations, which enable "EMS-dependent capabilities and systems to perform their functions in the intended environment without causing or suffering unacceptable interference."[2] While technical solutions are in development to meet this critical need, joint force spectrum management is largely accomplished manually through Excel spreadsheets and frequency listings. The manual processes used to manage the increasingly congested EMOE depicted in figure 3 are the antithesis of simplicity and should concern the warfighter.

To better manage this process, the joint force is developing JEMSO doctrine to guide the growing dependence on reliable EMS access. According to Joint Doctrine Note 3-16, *Joint Electromagnetic*

Figure 2. Visualization of Cyberspace and the Electromagnetic Spectrum in an Operational Environment



Legend

BDE: brigade
BN: battalion
CCMD: combatant command
DIV: division
DOD: Department of Defense
EW: electronic warfare
HSMCF: home station mission command facility
NEC: network enterprise center
PTT: push to talk
RHN: regional hub node
UAS: unmanned aerial system
- - International boundary
⊗ Network node
— Non-attributed network
····· Satellite transport

Source: U.S. Army Field Manual 3-12, *Cyberspace and Electronic Warfare Operations* (Washington, DC: Headquarters Department of the Army, April 2017), 1-3.

Spectrum Operations, "[JEMSO] are military actions undertaken by two or more Services operating in concert to exploit, attack, protect, and manage the EMOE. These actions include all joint force transmissions and receptions of electromagnetic (EM) energy."[3] The EMS is critical to the military's ability to execute operations and plays a similarly vital role in civilian infrastructures. The United States and its highly interconnected society are particularly exposed to a variety of EMS-related attacks, ranging from degraded communications and disrupted banking and financial transactions to interrupted electricity distribution. This dependency extends to U.S. military forces. In fact, the next armed conflict may be won or lost based on the fight for EMS superiority.[4]

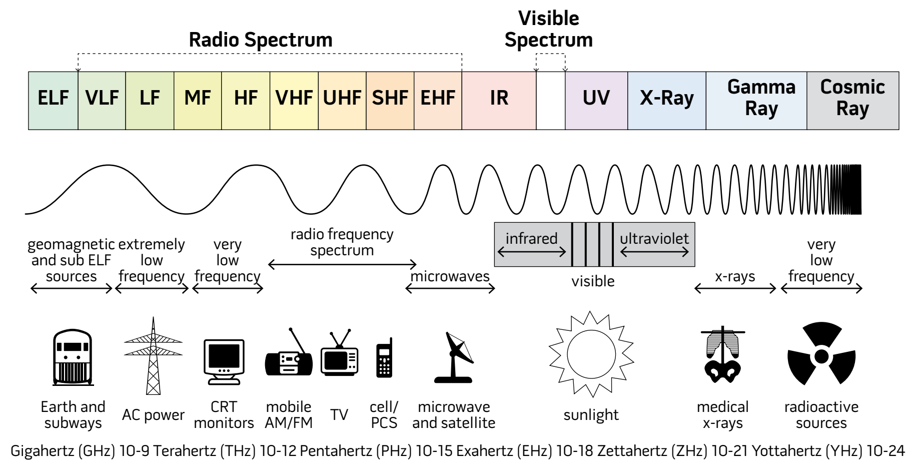
Adversaries are cognizant that effective EM measures during combat operations are vital to victory and may offset the military advantages enjoyed by the United States and its allies. The EMOE also provides an avenue for an adversary to influence the U.S. homeland in ways not possible during earlier conflicts. Near-peer competitors are incorporating progressive and innovative technologies that pose significant challenges to C2 and the infrastructures used in it.

The Defense Spectrum Organization (DSO) is the Department of Defense (DOD) Center of Excellence for spectrum management. DSO provides data-focused analytic expertise for military commanders, partners, and allies to enable spectrum management.[5] The analyses bolster the CCDR's ability to visualize and effectively employ operational capabilities within a complex electromagnetic environment. Comprehensively understanding the dynamic EMOE is vital for a CCDR to effectively shape and dominate the EMS and improve the capacity to identify, confront, circumvent, communicate, synchronize, and operate effectively.

The process employed to mitigate EMS fratricide is the joint restricted frequency list (JRFL), a "time and geographically oriented listing of . . . functions, nets, and frequencies."[6] However, the JRFL is still a list and does not readily improve a CCDR's ability to recognize EMS fratricide or visualize how the interference is affecting the battlefield. The current process to manage spectrum fratricide and interference is to file a report with the Joint Spectrum Interference Resolution (JSIR) program, which "identifies, reports, analyzes, and mitigates or resolves incidents of EMI [electromagnetic interference]."[7] Spectrum managers use the manual JSIR process to "report and diagnose the cause or source of all EMI (intentional/unintentional)."[8] The JSIR process quickly loses utility and effectiveness when facing a near-peer competitor attempting to affect the EMS in his favor or in a congested EMOE with constant EMI. In a contested or congested EMOE, friendly EMS fratricide and intentional interference by an enemy force are nearly indistinguishable.

With the 2019 JEMSO doctrine release, joint force commanders should expect improved integration of EMS operations. This doctrine reorganizes CCDR staffing functions and processes to recognize, report, and react to EMS interference sources; however, it does not singularly boost capacity or dramatically improve subject matter expertise running JEMSO cells. Humans have a limited ability to process the continually expanding amounts of EMS-related information in the EMOE. Additionally, humans manually processing the signal data lack the information quality required to visualize and understand the modern EMOE in battle-relevant time frames. The future of EMOE management hinges on system automation being able to inherently sense, display, and eventually modify friendly EMS-dependent systems operations to adapt to interference. Automated sensing and decisionmaking solutions must be employed to understand and visualize a complex EMOE and enable decisionmaking within the EMS that maximizes combat capability.

Figure 3. The Electromagnetic Spectrum



Legend

AC: alternating current
AM: amplitude modulation
CRT: cathode ray tube
EHF: extremely high frequency
ELF: extremely low frequency
EMF: electromagnetic field
FM: frequency modulation
HF: high frequency
IR: infrared
LF: low frequency
MF: medium frequency
PCS: personal communication system
SHF: super high frequency
TV: television
UHF: ultrahigh frequency
UV: ultraviolet
VHF: very high frequency
VLF: very low frequency

Current Initiatives

While the concepts and doctrine associated with JEMSO provide the joint force with necessary processes and a foundation for improving a CCDR's ability to see, understand, and make sense of the EMOE, the underlying technology is crucial to operationalizing the EMS as a warfighting capability. Even with the best trained personnel, processes, and plans, the future operating environment will be so complex that our ability to sense and orient the force to the EMS actions of a near-peer competitor will be virtually impossible. Numerous studies have determined that the character of war will continue to be increasingly reliant on the force's ability to sense and make sense of information. Workshops and war games repeatedly find that the ability to collect, process, and disseminate accurate battlefield intelligence to the right decisionmakers provides a key decisive edge.[9] To address this critical shortfall, DOD recognizes that the joint force must rapidly evolve in both its battlespace awareness and EMS agility to adequately compete in the next conflict. Legacy systems and engineering designs carried the force to where it is today, but the future promises known and unknown complex challenges that will test our ability to decisively act and react to changes in the competitive environment.

Before a discussion regarding active projects seeking to address the challenges faced in the EMS can commence, it is important to briefly discuss AI and ML. AI is an umbrella term used to describe a family of technologies and techniques seeking to allow machines to respond to external stimulation as humans might, with "contemplation, judgment, and intention."[10] Others take this idea one step further by broadly defining the qualities such systems and techniques must have. John Allen and Darrell West assert that AI systems should have "intentionality, intelligence, and adaptability."[11] As a recognized sub-discipline of AI, ML seeks to make sense of massive troves of data using computers that can react without running explicit rules-based programming functions. Essentially, the computers are deriving key relationships by learning from the data rather than being told what is important.[12] There are a variety of other ML techniques with a broad range of utility and effectiveness, but a deeper discussion of the full breadth and depth of AI and ML is beyond the scope of this article.

As the world continues to blur the boundary between possible and impossible with AI, DOD recognizes it must be at the forefront of the potentially disruptive technology. In June 2018, former Secretary of Defense James Mattis reorganized responsibility for DOD's AI initiatives from the Under Secretary of Defense for Research and Engineering, Michael Griffin, to DOD's Chief Information Officer, Dana Deasy, under a new organization, the Joint Artificial Intelligence Center (JAIC). The JAIC assumed coordination responsibilities for any AI-related project over $15 million, while the Services or sponsoring agencies maintain responsibilities for any project under $15 million.[13] Additionally, DOD released its 2018 AI strategy. The strategy, clearly informed by the other major national security strategies, broadly directs the Department to accelerate the adoption of AI while acknowledging that the technology will almost certainly change how DOD conducts business in potentially profound and unexpected ways.[14]

As DOD finally shines a spotlight on these disruptive and transformative technologies and acknowledges the need for coherent national AI strategies, research and development focused on utilizing AI and ML to improve how the United States leverages the EMS is increasingly important. One such project is the Defense Advanced Research Projects Agency (DARPA)–sponsored Radio Frequency Machine Learning System (RFMLS). RFMLS's goal is to "develop the foundations for applying modern data-driven machine learning to the RF [radio frequency] spectrum as well as to develop practical applications in emerging spectrum problems."[15] The effort sought to achieve four specific objectives. First, the system or system of systems should have the ability to learn features in order to directly use sensor data. Second, the system should be able to determine what EMS data are most important while

Marines from 2nd Radio Battalion, II Marine Expeditionary Force Information Group, and a Norwegian army electronic warfare operator employ Wolfhound Handheld Threat Warning System during Integrated Training Exercise 5-19 at Marine Corps Air Ground Combat Center, Twentynine Palms, California, July 30, 2019 (U.S. Marine Corps/Cedar Barnes)

simultaneously being able to recognize new signals of interest. Third, the system should be able to adaptively reconfigure sensors automatically to achieve optimum performance under given prevailing conditions. Finally, the system should have the capability to learn to synthesize and transmit entirely new engineering strong-motion ESM waveforms.[16] Another DARPA initiative is the Adaptive Radar Countermeasures (ARC) program. This program seeks to leverage ML and advanced signal processing to dynamically characterize a potential radar threat, even one never observed; synthesize a countermeasure (for example, conduct jamming); and then evaluate the countermeasure's battlefield effectiveness.[17]

Thanks to programs like RFMLS and ARC, the pace of EMS operations and our reliance on them will only increase. Near-peer competitors will attempt to exploit joint force EMS dependency, seeking to isolate systems specifically designed to use the EMS to optimize and integrate warfighting functions. The complexity of the environment requires that today's CCDR can understand, visualize, and act within the EMS to fully employ the broad capabilities of their fighting forces.

This is where the utility of AI- and ML-enabled EMS visualization systems can truly impact the total force operations by recognizing and reacting to a fluid EMOE. By integrating systems that can communicate among themselves without operator intervention and can incorporate the necessary bits of information that otherwise would be background noise to the human operator, improvements can be made in the ability to sense EMS actors and emissions. By applying a variety of models, AI- and ML-assisted systems can begin to categorize individual emissions and their impacts to friendly force EMS operations. With that said, the ability of AI and ML systems to access, process, and report on the EMS poses some operational challenges.

The Future Need

Incorporating AI into the EMOE visualization and understanding process will support the growing speed of JEMSO; however, AI, ML, and deep learning models depend on reliable and trusted data to ensure learning is not corrupted. The dependence on data in both quality and quantity poses the greatest risk to integration of AI and ML technologies into the JEMSO processes. In June 2015, the U.S. Army Research Laboratory conducted a workshop to visualize the tactical ground battlefield in 2050 and reported that "the roles of information technologies will co-evolve (that is, will influence and be influenced by) future concepts and technologies for key warfighting functions, including seeing (sensing), understanding, communicating . . . capabilities that are involved in obtaining, collecting, organizing, fusing, storing, and distributing relevant information as well as the capabilities associated with C2 functions and processes including reasoning, inference, planning, decisionmaking."[18]

Up to this point this article has discussed the current limitations in sensing and understanding the EMOE and the role of AI and ML technologies and how they can change the tools available to accomplish these tasks. In order to realize the potential advantages offered by introducing AI and ML capabilities into our JEMSO C2 systems, there must be clarification of the basic requirements for sensing, visualizing, and informing decisions regarding the EMS.

First, sensing is the process of collecting, routing, and storing information that will form the building blocks for further analysis and processing. Using EMS sensors to facilitate this is not a new concept. Nearly every fielded system in the military today has an aperture designed to facilitate its own limited EMS sensing requirements. So how does application of AI and ML change the role of these apertures to enable enhanced and centralized EMS sensing? More specifically, what level of EMS sensing is required to facilitate a CCDR's decisionmaking regarding JEMSO? The answer is not in the apertures; instead, it lies in how one connects and moves the information to a central processing system enabled by AI and ML. This information or data is working through the AI and ML models to provide the learning context for these systems, which builds understandable visualization, improves them over time, and ultimately allows a CCDR to understand where, how, and to what effect all EMS actions are having on the EMOE.

Imagine the EMOE as an ecosystem. Within it, the AI and ML would represent a central nervous system, connecting the individual sensor neurons and processing inputs from them to understand the environment. In this same ecosystem, the data from these sensors could be represented by the blood that fuels the decisionmaking and learning models for the AI and ML systems. Today, each individual aperture is isolated, reporting only to its own internal and limited system for a designed function related to the same individual system. By integrating AI and ML processes into our JEMSO systems, we can connect these apertures, or more accurately the data they are sensing becomes connected, to a central nervous system capable of moving and storing the information meeting multiple EMS purposes simultaneously. This idea is commonly referred to as the "big data" concept.[19] In the simplest terms and for the scope of this article, two types of data concepts are examined, "big" data and "deep" data. Arguments can be made on the advantages and disadvantages of these data sets. In truth, battlefield commanders will require both.

Let us begin by clarifying in simple terms the differences between big and deep data sets. The working definition of *data* for our discussion is bits of information that can be combined to depict a pattern of information that can be used to visualize the EMS. In this simple definition, an individual data point is not of much value to improving AI and ML technologies or recreating near real-time EMS visualization. To do this, automated systems will require multiple data sets or groupings of these individual data points that, when combined, begin to tell a story about the nature of the EMOE. Common approaches for collecting these data sets are where the terms *big* and *deep* enter the discussion. For the purpose of this article, *big data* is used to reference the collection of massive quantities of data sets from across a wide set of sensors. The advantage of big data in this definition is in its ability to scrape a vast quantity of data points from the EMOE for any snapshot in time. It does this by integrating and pulling shallow data sets from multiple sensors for a defined time slice and providing these individual data points to the AI ecosystem. The AI/ML system can rapidly compare these snapshots, using them to recognize patterns occurring in the environment.

While the idea of having thousands of EMS sensors each providing inputs from their individual apertures' perspective into a visualization system may initially sound like an easy answer, the issue is more complex. Moreover, commanders make decisions not on data but rather on intelligence, and "it is the job of the Intelligence Community to analyze, connect, apply context, infer meaning, and ultimately make analytical and operational judgments based on all available data."[20] Since data in its rawest form builds the individual pixels of information to be used by AI/ML systems to learn, the sources and quality must be controlled to reduce risk and prevent unwanted manipulation. Failure to ensure the quality of data sets can change the processing and dissemination of the intelligence being produced. Conversely, *deep data* sets are used to describe the detailed quality of an individual data point against a singular purpose or target over time to build behavioral relationships and to add depth of understanding.[21] Through deep or analyzed data, EMS visualization takes on context and meaning. By combining both deep and big data sets into our ML and deep learning models, EMS visualization systems can rapidly sense the EMOE and focus intelligence analysis efforts against it to enable meaningful understanding. In other words, if big data provides the *what*, then deep data provides the *so what*. With both the what and the so what bits of information, intelligence processes can be streamlined, resulting in actionable EMS visualization and understanding informing the CCDR decision processes. Therefore, while the idea of big data does offer a capability to rapidly sense the EMOE, it must be measured and weighed against deep data sets to reduce the risks of data corruption and to provide the intelligence necessary to understand the EMOE.

Next is communicating this information in a way that enables a commander and staff to quickly understand it, enabling them to make informed decisions on JEMSO. Today, our forces employ many variations of EMS modeling capabilities to help them build graphical understanding and visualization of the EMS—everything from 3D modeling to waterfall spectrum charts and maps with specific emitter graphics and details. However, all of these visualization tools are costly in time and labor and do not have the capacity to work with the vast amount of data available through an AI-enabled EMS sensing solution. To reduce the processing time required and accurately relay the EMOE

Marine with electronic warfare liaison element, Marine Rotational Force–Europe 19.2, Marine Forces Europe and Africa, prepares for tactical extract during exercise Valhalla in Setermoen, Norway, June 17, 2019 (U.S. Marine Corps/Larisa Chavez)

at the speed of battle, these modeling tools must leverage or become a function of the same AI learning systems used to collect and process the EMS data/information. To simplify, the same AI and ML technology that is integrating the EMS abilities to sense, visualize, and understand can simultaneously direct refined intelligence analysis and graphical modeling programs. Not only can it do this, but it also should do this to provide CCDRs a visual depiction of what is being detected in the EMS, relationships and behaviors tied to the detections, and how their forces are responding. Admittedly, this may present some risk by prematurely acting on information before detailed intelligence analysis is accomplished. To mitigate this risk, human expertise is required in the processes.

The human expertise residing in the JEMSO planning and execution cells will serve to coordinate these actions, but the design of the visualization must be simplified to allow for immediate and detailed understanding. To put this in context, today within most of the land, maritime, air, or space operations centers, a CCDR can look up to the big screens and quickly see and understand where forces are and what actions are being performed. However, there is not visualization of what the EMS looks like around them or what is being done within it to ensure they are connected to the rest of the force. In a limited engagement, we can get away with this lack of understanding and visualization, but against a near-peer competitor we will quickly see our forces isolated from the rest of the military systems supporting them if we fail to visualize and understand the EMOE.

Conclusion

Let us again imagine you are a CCDR equipped with the very best capabilities today's military can offer. But now add into your tool kit a C2 system that incorporates emerging JEMSO doctrine and is enabled by AI and ML technologies. These technologies rapidly connect the thousands of apertures across the battlefield and report back to command systems, providing both big and deep data sets—data sets that can be applied to the AI and ML systems to increase system learning of the EMOE in detail. Armed with these systems and your network of data providers, you can rapidly detect, report, and produce visualization tools that allow you to understand the changes in your EMOE as they are reported, enabling you to make effective and timely decisions to protect and ensure your force access to the EMS. Given this system, the CCDR sees and understands the EMOE, quickly recognizing and mitigating near-peer competitors' attempts to affect friendly force spectrum assurance. Having gained an increased understanding of the EMOE, the CCDR can mitigate EMS impacts and maximize the joint force's warfighting potential.

By integrating AI and ML systems into the JEMSO C2 doctrine and processes, a CCDR is better equipped to visualize and understand his EMOE at the speed of battle in the information age. The need for improved processes to sense and make sense of the EMS and how it is intertwined within our military and national networks has been identified as critically important by all levels of our strategic guidance, yet DOD has no solutions currently fielded to address the issues. By incorporating smart and automated systems that apply a variety of learning models, we can improve the EMS visualization processes and better understand the nature of the information fueling these systems. The Defense Department can reduce the risks associated with capacity saturation by balancing between deep and big data solutions that enable us to understand and visualize the EMOE. The safety and combat effectiveness of the joint fighting force demand AI solutions that preserve the capacity to sense and make sense of an incredibly complex electromagnetic operating environment. Now is the time to lift the electromagnetic fog of war. **JFQ**

Joint Publications (JPs) Under Revision (to be signed within 6 months)

JP 1-0, *Personnel Support*

JP 2-0, *Joint Intelligence*

JP 3-05, *Special Operations*

JP 3-26, *Combating Terrorism*

JP 3-40, *Countering WMD*

JP 5-0, *Joint Planning*

JP 6-0, *Joint Communications System*

JPs Revised (signed within last 6 months)

JP 1, *Doctrine for the Armed Forces of the United States*, vol. 1

JP 3-09, *Joint Fire Support*

JP 3-09.3, *Close Air Support*

JP 3-10, *Joint Security Operations*

JP 3-29, *Foreign Humanitarian Assistance*

JP 3-30, *Joint Air Operations*

JP 3-31, *Joint Land Operations*

JP 4-09, *Distribution Operations*

JP 4-10, *Operational Contract Support*

Notes

[1] The *electromagnetic operating environment* (EMOE) is defined as "the background [electromagnetic] radiation and the friendly, neutral, and adversarial electromagnetic [activity] within the [electromagnetic area of influence] associated with a given operational area." See Chairman of the Joint Chiefs of Staff Memorandum 3320.01C, *Joint Electromagnetic Spectrum Management Operations in the Electromagnetic Operational Environment* (Washington, DC: The Joint Staff, December 14, 2012), appendix D to enclosure C, C-D,1. The EMOE is a complex composite of the electromagnetic conditions, circumstances, and influences that affect the employment of capabilities and the decisions of the commander.

[2] Joint Publication 6-01, *Joint Electromagnetic Spectrum Management Operations* (Washington, DC: The Joint Staff, March 20, 2012), viii.

[3] Joint Doctrine Note (JDN) 3-16, *Joint Electromagnetic Spectrum Operations* (Washington, DC: The Joint Staff, October 20, 2016), I-1.

[4] Ibid., v.

[5] See Defense Information Systems Agency, "About DSO" [Defense Spectrum Organization], available at <https://storefront.disa.mil/kinetic/disa/service-catalog#/forms/about-dso>.

[6] JDN 3-16, C-1.

[7] Ibid., I-9.

[8] Ibid.

[9] Alexander Kott et al., *Visualizing the Tactical Ground Battlefield in the Year 2050: Workshop Report*, ARL-SR-0327 (Adelphi, MD: U.S. Army Research Laboratory, June 2015), 22.

[10] Shukla Shubhendu and Jaiswal Vijay, "Applicability of Artificial Intelligence in Different Fields of Life," *International Journal of Scientific Engineering and Research* 1, no. 1 (September 2013), available at <https://pdfs.semanticscholar.org/2480/a71ef5e5a2b1f4a9217a0432c0c974c6c28c.pdf>.

[11] Darrell M. West and John R. Allen, *How Artificial Intelligence Is Transforming the World* (Washington, DC: The Brookings Institution, April 24, 2018), available at <www.brookings.edu/research/how-artificial-intelligence-is-transforming-the-world/>.

[12] Daniel Faggella, "What Is Machine Learning?" *Emerj*, February 19, 2019, available at <https://emerj.com/ai-glossary-terms/what-is-machine-learning/>.

[13] Sydney J. Freedberg, Jr., "Joint Artificial Intelligence Center Created Under DOD CIO," *Breaking Defense*, June 29, 2018, available at <https://breakingdefense.com/2018/06/joint-artificial-intelligence-center-created-under-dod-cio/>.

[14] *Summary of the 2018 Department of Defense Artificial Intelligence Strategy: Harnessing AI to Advance Our Security and Prosperity* (Washington, DC: Department of Defense, 2018), available at <https://media.defense.gov/2019/Feb/12/2002088963/-1/-1/1/summary-of-dod-ai-strategy.pdf>.

[15] Radio Frequency Machine Learning Systems program, Defense Advanced Research Projects Agency–funded program solicitation, Duke University Web site, 2017, available at <https://researchfunding.duke.edu/radio-frequency-machine-learning-systems-rfmls>.

[16] Ibid.

[17] Adaptive Radar Countermeasures, BAE Systems Web site, 2017, available at <www.baesystems.com/en-us/product/adaptive-radar-countermeasures-arc>.

[18] Kott et al., *Visualizing the Tactical Ground Battlefield in the Year 2050*, I-2.

[19] This reflects the authors' generalized definition of *big data* as applied to the context of this article only.

[20] *The AIM Initiative: A Strategy for Augmenting Intelligence Using Machines* (Washington, DC: Director of National Intelligence, December 2018), 1, available at <www.dni.gov/files/ODNI/documents/AIM-Strategy.pdf>.

[21] This reflects the authors' generalized definition of *deep data* as applied to the context of this article only.