A Streamlined Approach to Analyzing Next-Generation Electronic Warfare Capabilities

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ABSTRACT

With a rich history dating back over a century, electronic warfare has become a powerful tool at the warfighter's disposal. However, as technology continues to advance, so must the capabilities of electronic warfare systems and the tools used to evaluate them. A team at the Johns Hopkins University Applied Physics Laboratory (APL) leveraged a unique combination of technical and operational expertise to develop a streamlined analysis approach to minimize turnaround time for analysis. This article overviews this approach and highlights a robust digital signal processing tool providing quick and thorough analysis results for mission-critical and operationally relevant test data.

INTRODUCTION

With a growing list of industries competing for space in a limited electromagnetic spectrum, signal processing technologies have been forced to leverage recent advancements in computing speeds and novel machine learning algorithms to keep up with demand.[1] While this rapid advancement has undoubtedly improved our lives on many levels, it has also created a dynamic and multifaceted electromagnetic landscape that needs to be carefully navigated. The complexities of our modern radio-frequency environment can be leveraged by adversaries for malevolent purposes. This threat is particularly important for warfighters operating in contested and hostile environments. The potential for mal-intent, combined with rapidly evolving and readily available technology, has driven a need for next-generation electronic warfare capabilities to incorporate signal processing technologies that are both flexible and reliable.

NATO policy defines electronic warfare as "a military action that exploits electromagnetic energy, both actively and passively, to provide situational awareness and create offensive and defensive effects."[2] Under such general guidelines, it can be argued that electronic warfare is as old as the fabled account of Archimedes burning the Roman fleet by reflecting the sun's light in 213 BC.[3] In actuality, the dawn of electronic warfare is far more recent, dating back to the Russo-Japanese War (1904–1905) where radio jamming was first successfully employed in combat.[2,4,5] During World War I (1914–1918), the use of radio air-ground communications proved critical for both reconnaissance and artillery spotting.[5] In the years preceding World War II (1939–1945), advancements such as radio navigation and radar, which were vital throughout the war,[4] allowed for further development of tools and systems, including high-frequency direction finding, electronic countermeasures, anti-jamming electronic counter-counter measures, and electronic intelligence.[4,5]

The threats faced from the Cold War (1947–1991), the Korean War (1950–1953), and the Vietnam War (1955–1975) prompted further progress in electronic warfare tactics and technologies, including the invention of transistors, traveling wave tubes, spiral antennas, airborne electronic warfare systems, and radar homing and warning systems.[4,6] From the first Gulf War onward, computers and networked information have become highly integrated into modern warfare systems and the ways which missions and wars are executed.[4,5] This integration requires electronic warfare systems and strategies to advance accordingly to maintain dominance within modern radio-frequency landscapes. To accomplish this goal, systems must undergo extensive and complex testing to ensure operational and mission success. Testing for electronic warfare systems comes with many challenges—including technical, logistical (budget, resources, schedule, etc.), and security compliance challenges, particularly with testing "advanced techniques." Technical challenges arise when cutting-edge hardware and signal generation need to be met with cutting-edge testing environments and signal processing methods.

Because modern electronic warfare systems operate in dynamic environments, it can be difficult to plan tests that accurately replicate real-world scenarios. Some programs may opt to have multiple testing sites that can provide different testing environments, such as anechoic chambers or over-the-air testing. To maximize efficiency across these sites, a design of experiments approach can be used, and test priorities must be flexible as unexpected discoveries about the system unfold. Communication across these test sites throughout planning, execution, and analysis is also imperative, as it can be difficult to determine sources of error. Errors can be caused by the test setup, test points designed to operate outside of what is expected from the system, human error, or system malfunction, to name a few. Being able to quickly determine the source allows the larger testing community to identify and remedy common anomalies while meeting budget and schedule constraints.

Additional data analysis complexities may arise from different testing sites since recording equipment may store data in a variety of formats, sometimes proprietary. Systems under test can also have complicated test points that include multiple assignments with overlapping features, data rate limitations, and even sophisticated system logic for assignment allocation. Solving these challenges requires a robust analysis solution that is streamlined and automated across all test sites. The ability to quickly turn around results will be critical to ensuring operational and mission success for upcoming electronic warfare systems. With this in mind, our team leveraged a unique combination of technical and operational expertise to develop an analysis tool capable of addressing these challenges.

The remainder of this article presents an overview of the team and where it fits within the overall APL hierarchy, outlines the four steps to a streamlined analysis pipeline, and offers a brief example to highlight some of the tools' capabilities. It concludes with a brief look toward the future.

THE VISION OF OUR TEAM AT APL

> Since the U.S. Navy lost its first aircraft to a surface-to-air missile system in the skies over Vietnam, APL has played a key role in the development of tactics and electronic countermeasures to deal with the threat of foreign air defense systems. Working with naval aviation and industry partners, APL designed and developed prototypes of systems to support the Navy EA-6B Prowler as well as its successor, the EA-18 Growler—electronic warfare aircraft equipped to suppress enemy defenses in support of U.S. and allied operations.
>
> APL continues to be deeply involved in Navy electronic warfare operations through its work with the Jammer Technique Optimization (JATO) group. This consortium of military, government, and independent research and development organizations provides engineering, development, and test support to evaluate, validate, and operate radar and communications jamming techniques.
>
> —APL Annual Report 2017[7]

As the country's largest university-affiliated research center (UARC), APL has acted as a trusted adviser and technical expert to the United States government for nearly 80 years.[8] As such, it should come as no surprise that within APL's diverse portfolio is an abundance of work focused on, and related to, electronic warfare. In fact, APL's Force Projection Sector has multiple groups dedicated solely to electronic warfare systems and advanced electronic attack development, as well as a dedicated electronic warfare program area within its Precision Strike Mission Area.

The authors' data analysis team is just one of many teams that are deeply dedicated to this mission area and use their unique talents to support the test and evaluation of next-generation electronic warfare systems. In short, they explore system behaviors and waveform generation to verify proper performance over many environments and parameters. These teams consist not only of scientists, mathematicians, and engineers but also of retired pilots, electronic warfare officers, and mission planners. The diversity of backgrounds lends itself to a holistic understanding of the big-picture mission objectives, the mission impacts of system behaviors, and sponsors' organizational needs. Our team's interactions can extend to the government test execution groups, ideally creating a triad of communication among APL, these government test execution groups, and our sponsor dictating test priorities. Given the diversity of systems and missions that this community supports, we developed a systematic, adaptable, streamlined, and automated approach.

OVERVIEW OF APPROACH

Results often need to be turned around quickly to inform subsequent test planning or execution, which may occur within a week of currently delivered data. Quick-look briefs created by APL have shown the test community which test conditions are compliant and which need further investigation in future test plans. Additionally, if changes can be made in the data collection process to more accurately capture system behavior, that information can be communicated to the test execution teams in a timely fashion. Figure 1 shows an overview of the testing life cycle, where test planning occurs first, followed by execution and then analysis. Analysis informs future test planning and execution, allowing the cycle to continue repeatedly.

Our team's data analysis approach can be broken down into four sequential phases: data collection and consolidation, preprocessing, analysis, and output. It has been specifically designed with the goal of minimizing turnaround time by maximizing the analyst's ability to quickly and accurately interpret results. Although these are obvious objectives for a data analysis pipeline, they are surprisingly difficult to efficiently attain, predominantly because these objectives often compete. More explicitly, for mission-critical results, the desire for a thorough analysis needs to be delicately balanced against the need to expedite results.

To achieve this balance, we designed a framework that prioritizes the user interface at the beginning and end of the analysis pipeline, allowing for a majority of analysis to proceed unimpeded without significant need for a user in the loop. Prioritizing the user interface at the end of the pipeline allows for efficient examination of analysis results to flag irregular or anomalous behavior. Therefore, when we began developing our analysis pipeline, we started by examining the required analysis end products and determined the steps needed to create those analysis products. Likewise, prioritizing the user interface at the beginning ensures that the analysis pipeline is correctly initialized, allowing for data to be rapidly and reliably reanalyzed as needed.

The remainder of this section briefly steps through the four phases of the analysis process (outlined in Figure 2), explains how we approach each in this design, and provides an example highlighting a subset of the analysis capabilities.

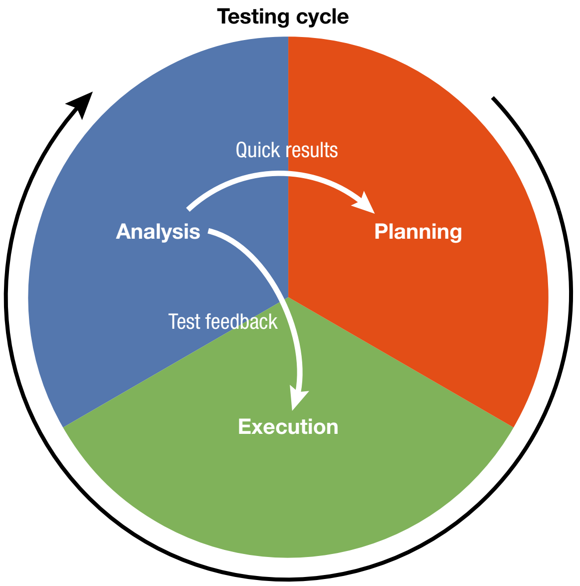


Figure 1. Overview of the testing life cycle. Test planning occurs first and is followed by execution and then analysis. Analysis informs future test planning and execution, allowing the cycle to continue repeatedly.

Data Consolidation

Data consolidation is required to ensure that the data files from different sources are standardized before use of our analysis tool. Additionally, our primary focus is to verify that systems are working as intended; as such, a priori information such as commanded waveform parameters is required for each data set. This information not only allows for a precise error quantification between assigned and actual parameter values but also

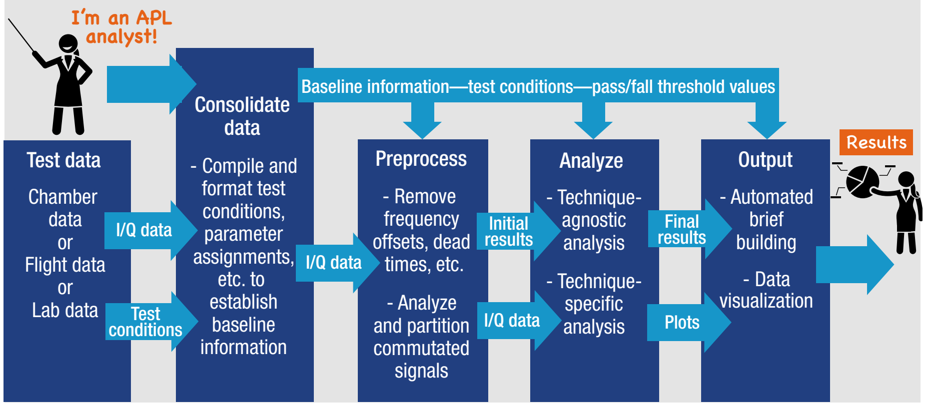


Figure 2. Outline of the analysis pipeline. This overview shows how test data and analyst input are used to extract and output analysis results. I/Q, in-phase/quadrature-phase.

significantly reduces the challenges of analyzing a given set of data. That being said, members of the test and evaluation team are not responsible for collecting data. Rather, data files are sent to us from a variety of test sites across the country. While there are benefits to having multiple data sources, there are also drawbacks. One particular hurdle that we have had to address is a lack of standardized conventions in naming, storing, logging and sending data—between test sites and even between test events at the same site.

This lack of standardization is problematic for a tool requiring expected waveform information and signal in-phase/quadrature-phase (I/Q) data to be input in a specific manner. As such, a primary and ongoing effort is the consolidation of various data sources into detailed and consistent files that can be fed into the analysis toolbox. Streamlining this process heavily depends on the ability to correctly parse information from different data and header files, test logs, system output files and even hand-written notes. Therefore, there is no one-size-fits-all solution to automate this process and, even under the best of circumstances, the solution requires at least some user input to ensure that information has been correctly partitioned. Fortunately, as a team is exposed to data sets with new naming and logging conventions, the development of a diverse set of tools allows the rapid parsing of pertinent information from a broad set of data formats in the future.

Preprocessing

Following data consolidation is data preprocessing. The primary purpose of this step is to prepare data sets for processing by the analysis toolbox, which is designed to analyze individual waveform parameters at a single assignment frequency. The goal of all analysis performed in this step is to divide complex data collections involving multiple waveform types at different radio frequencies into individual waveform components to be analyzed.

Currently, the preprocessing includes the following functions:

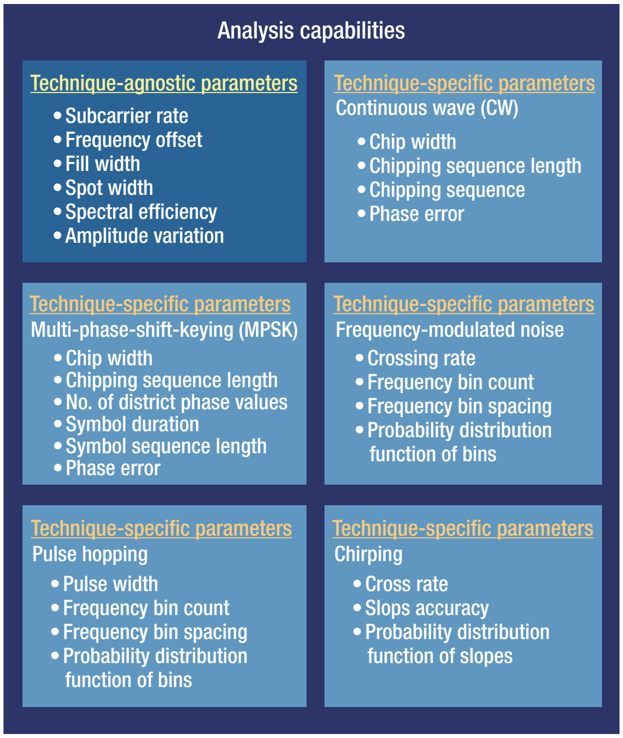
- Verifying that the necessary folders for loading and saving data exist
- Searching data sets for periods of time with no radiated output from the system (i.e., blanks) and removing those portions from the I/Q data
- Determining whether data sets correspond to time-commutated techniques, and if so
    - Analyzing commutation parameters (time to switch from one technique to another, or dead time; time radiating each technique, or dwell time; etc.) and saving initial analysis results
    - Partitioning single data sets into multiple data sets corresponding to each of the commutated techniques
- Estimating and removing any center frequency offsets that may exist and storing the offset value for future analysis
- Saving preprocessed data as MATLAB .mat files

While this procedure is mostly automated, the blank-removal and time-commutation-analysis steps currently require minimal user input to identify an appropriate threshold value between distinct portions of data. We attempted to automate these steps, but the variation in signal levels between different data sets presents an ongoing challenge.

Analysis

The analysis toolbox, which is the crux of this work, is the next level of the pipeline. At this level, the consolidated information files are combined with the preprocessed I/Q data to provide parameter analysis for a swath of different waveforms. Designed to be fast and thorough, this library of code constitutes a powerful tool capable of decoupling numerous overlapping parameters to provide a comprehensive analysis of the waveform. Furthermore, users may expedite results by selecting a subset of preprocessed test points that will be analyzed and determining the types of analysis tools that will be "on" or "off" during the analysis.

The analysis process can be broken down into two steps: (1) analyzing parameters that are agnostic to technique



Analysis capabilities

Technique-agnostic parameters
- Subcarrier rate
- Frequency offset
- Fill width
- Spot width
- Spectral efficiency
- Amplitude variation

Technique-specific parameters
Continuous wave (CW)
- Chip width
- Chipping sequence length
- Chipping sequence
- Phase error

Technique-specific parameters
Multi-phase-shift-keying (MPSK)
- Chip width
- Chipping sequence length
- No. of district phase values
- Symbol duration
- Symbol sequence length
- Phase error

Technique-specific parameters
Frequency-modulated noise
- Crossing rate
- Frequency bin count
- Frequency bin spacing
- Probability distribution function of bins

Technique-specific parameters
Pulse hopping
- Pulse width
- Frequency bin count
- Frequency bin spacing
- Probability distribution function of bins

Technique-specific parameters
Chirping
- Cross rate
- Slops accuracy
- Probability distribution function of slopes

Figure 3. Current analysis capabilities. Capabilities include parameters that are not specific to any given waveform and those corresponding to the five waveforms of primary interest to the team.

type, and (2) analyzing technique-specific parameters. The first category includes parameters such as subcarrier rate, center frequency offset, fill width, spot width (coverage), spectral efficiency, and spectral amplitude variation, which are applicable to any waveform that our team may analyze. The second category contains a more extensive list of parameters that can be divided into five sub-categories depending on the waveform technique. The full list of parameters that can currently be analyzed in each of these sub-categories is shown in Figure 3.

After all desired analysis has been completed, results are saved in data structures with a specifically designed storage hierarchy. This approach allows for tools at the back end of this pipeline to quickly and reliably pull the results for analysts to review. Here is where the team's expertise in waveform analysis is utilized to its fullest extent. Any unusual results are flagged for further investigation, and those test points and/or parameters are re-analyzed with a user in the loop to determine whether the irregularity is the result of a shortcoming in the analysis tools or an anomaly in the data. If the former, the problematic analysis code is promptly debugged, and the data is re-analyzed. If the latter, the anomalous behavior is investigated more thoroughly by the analysis team, in collaboration with subject-matter experts and test conductors, and included in the final analysis brief.

Output

The analysis pipeline is flexible so that it can be used to analyze a variety of platforms, and so the output (e.g., visualizations, diagrams, and presentations) can be customized. The user selects configuration files for each system at the beginning of analysis; these files contain information such as specified requirements for each technique that can be radiated from the system. Additionally, the team at APL has identified "operational impact" requirements. These requirements were specified by retired pilots, electronic warfare officers, and mission planners and help identify the most mission-critical specifications in our analysis. These configuration files tell the analysis tool to assign "pass" or "fail" to each specification being tested, and the results are then saved in a tree structure that can be parsed by other supporting tools.

The APL team developed two supplementary tools that parse the output structure to aid analysts. The first tool is a brief builder that automatically creates a presentation slide for each test point analyzed; each slide contains the technique spectra, assigned technique parameters, and a stoplight chart summarizing technique specification, operational impact requirements, and the resulting analysis pass/fail values. This tool has improved the efficiency and effectiveness of our analysis process, saving hours in developing briefs and providing a consistent presentation format that helps us identify anomalous behavior easily and allows our partner organizations and sponsors to quickly understand our results.

An additional tool created by the APL team is the Visual Aid for Radio-Frequency Signal Analysis (VARSA). VARSA allows users to quickly compare analysis results across different parameters in a test matrix and to identify any trends. A user can select plot types and features to plot, as well as color maps, to obtain the best chart for analysis.

These tools are generalized enough that they have been adapted outside of our team for analysis of any data using the generalized tree structure we created.

Example

To demonstrate some of the capabilities of the analysis tool, this section provides a brief example that is representative of the types of waveforms encountered in our analysis. The computer-generated data used in the example consists of two time-commutated assignments (i.e., the signal switches back and forth in time); the first assignment is a frequency-modulated noise technique with the center frequency chirped across the assignment bandwidth, and the second is a frequency-hopping pulse technique with the center frequency of the hop set chirped across a desired bandwidth. White Gaussian noise has also been added to the signal to produce surrogate data that are as realistic as possible. Figures 4–6 depict the analysis process.

The first step in this analysis pipeline is to partition the commutated signal (Figure 4) into two separate files corresponding to the constituent techniques (Figure 5). This is achieved in the preprocess step by utilizing the signal's instantaneous frequency (i.e., frequency over time) and power over time. Additionally, each of these separated signals is then "centered" in frequency to produce data sets that are easily analyzable.

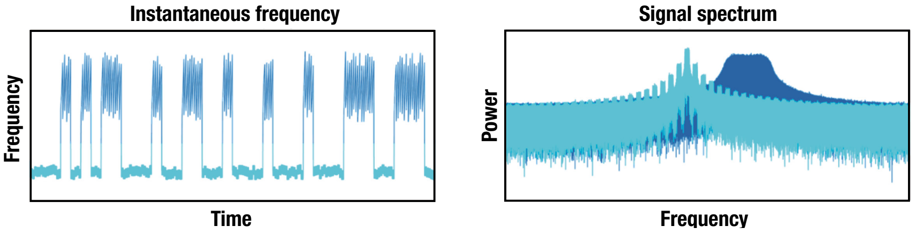


Figure 4. Received data. Unprocessed, time-commutated I/Q data consisting of two different techniques with various overlapping waveform parameters and modulations. Plots are color-coded to distinguish between the frequency-modulated noise technique (blue) and the frequency-hopping pulse technique (cyan).

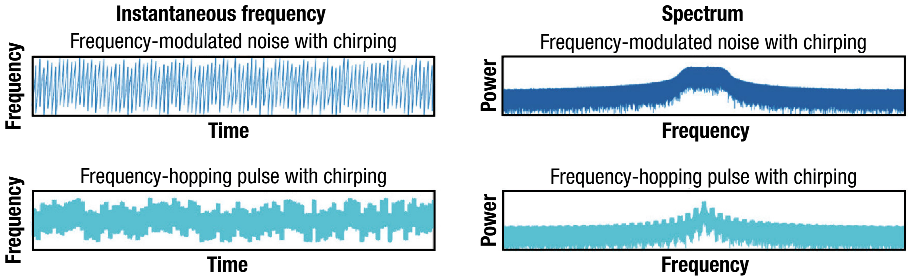


Figure 5. Preprocess step. Time-commutated techniques are divided into two separate data files. Center frequency offsets are removed so that each data set is centered at baseband.

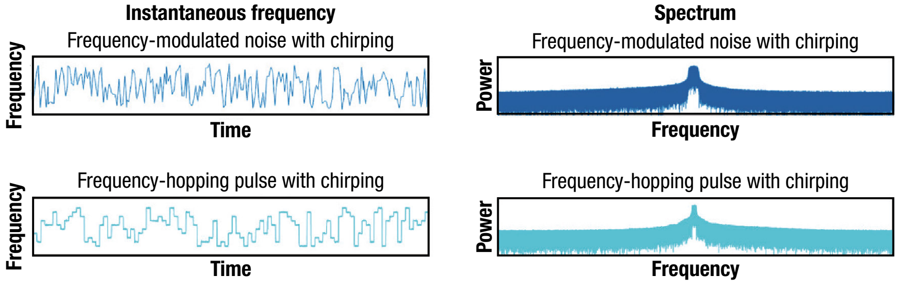


Figure 6. Analysis step. Overlaid chirping is removed from each data set and analyzed. The underlying techniques are revealed, allowing for a thorough analysis of each of the distinct waveforms.

Moving forward to the analysis step, the overlaid chirping modulations are removed from each signal's time-series (Figure 6). This process provides an accurate measurement of the chirp slope for comparison to the specified value, gives a clear picture of the underlying waveforms, and allows for the analysis process to accurately measure the technique parameters. After waveform-specific analysis has been completed, the results are systematically stored and saved for review by analysts.

Although succinctly stated, the above example demonstrates a powerful digital signal processing tool. The ability to sequentially peel back the layers of complicated waveforms not only allows for intricate analyses of numerous parameters, but it also enables testing teams to reduce the number of captured test points by overlaying multiple features and modulations into fewer signals. Together, these advancements increase throughput and decrease turnaround time, providing a quick and thorough analysis of mission-critical and operationally relevant data.

LOOKING TO THE FUTURE

Adversary sensors and command and control systems are becoming more difficult to locate and target, more agile in the waveforms and techniques they employ, and more capable in their ability to sense and react to the electromagnetic environment. Systems often use cognitive methods to operate effectively in the presence of electronic attack. To address these emerging complex threat systems, our electronic warfare capabilities must become more adaptive and more resilient to adversary countermeasures.

The future of electronic warfare is moving toward combinations of highly capable, distributed, and collaborative systems that learn on the fly and employ multi-domain capabilities of space, airborne, ground, and/or sea-based platforms to deliver effects (e.g., collaborative use of electronic attack and electronic support, decoys, and cyber). The desired end state is a set of capabilities that will effectively deny, degrade, deceive, and ultimately control the electromagnetic spectrum. These next-generation systems require the support of a highly functional test and analysis pipeline.

Although the functionality of the analysis pipeline we have developed thus far is extensive, it is not exhaustive. We are continually expanding the capabilities of the tool set to address new system capabilities, while simultaneously optimizing and reinforcing existing code to handle new or anomalous data sets. Some examples of newer analysis capabilities required to support future tests are simultaneous assignments, simultaneous communications and jamming, advanced jamming techniques, and integration of machine learning techniques to further reduce the need for users in the loop.

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REFERENCES

[1] D. Panhans, R. Schicht, F. Hamady, and T. Werlé, "The coming battle for spectrum," BCG Global, Feb. 11, 2020, https://www.bcg.com/publications/2020/coming-battle-for-spectrum.
[2] M. von Spreckelsen, "Electronic warfare—The forgotten discipline," Joint Air Power Competence Centre, Dec. 13, 2018, https://www.japcc.org/.
[3] A. A. Mills and R. Clift, "Reflections of the 'Burning mirrors of Archimedes'. With a consideration of the geometry and intensity of sunlight reflected from plane mirrors," *Eur. J. Phys.*, vol. 13, no. 6, pp. 268–279, https://doi.org/10.1088/0143-0807/13/6/004.

[4] A. C. Kucukozyigit, “Electronic warfare (EW) historical perspectives and its relationship to information operations (IO)—Considerations for Turkey.” Monterey, CA: Naval Postgraduate School, Sep. 2016.
[5] R. Schroer, “Electronic warfare. [A century of powered flight: 1903–2003],” *IEEE Aerosp. Electron. Syst. Mag.*, vol. 18, no. 7, pp. 49–54, 2003, https://doi.org/10.1109/MAES.2003.1226535.
[6] A. Price, *The History of U. S. Electronic Warfare.* Vol. 2. Alexandria, VA: Association of Old Crows, 1989.
[7] APL, *APL Annual Report 2017.* Laurel, MD: Johns Hopkins University Applied Physics Laboratory, 2017.
[8] “About APL.” Apr. 14, 2021. https://aplweb.jhuapl.edu/insideapl/Pages/About.aspx.

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