DSIAC JOURNAL

A Quarterly Publication of the Defense Systems Information Analysis Center

Volume 2 • Number 4 • Fall 2015

THE HISTORY, TRENDS, AND FUTURE OF

INFRARED TECHNOLOGY

PAGE 23

DSIAC JOURNAL

VOLUME 2 | NUMBER 4 | FALL 2015

Editor-in-Chief: Eric Fiore

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On the Cover:
The L-3 Sonoma EO's 1508M DragonEyes™ system provides wide-area MWIR tactical imagery for overwatch and critical event monitoring on fixed-wing, rotary-wing, UAV, or aerostat aircraft for airborne mission commanders. Credit: L-3 Communications.

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MESSAGE FROM THE EDITOR

ERIC FIORE

After I completed my undergraduate degree in the mid 1980s, my first job was with Martin Marietta Laboratories, where I worked with a team of scientists and researchers developing new infrared (IR) detectors. So, when I first read this quarter's feature article, I was overcome with nostalgia as the authors took me on an enjoyable stroll down memory lane. But what I found most remarkable was how far IR technology has advanced since then and how it continues to evolve and advance today. IR sensors and systems of the future will not only count and process photons; they will also have the ability to understand what they are looking at and make decisions. In this issue of the *DSIAC Journal,* we discuss how the U.S. military is working to maintain its technological advantage in this area as it moves from its age-old position of "owning the night" to having to share it with others.

In our feature article, authors Ralph Teague and David Schmieder provide a historical overview explaining the origins, growth, and future of the IR industry in the United States. This historical perspective is an enlightening narrative that explains how the technology evolved from simple crude devices to complex systems capable of seeing what is otherwise invisible. The article concludes with discussions of some of the hottest new technologies and offers a glimpse of what we can expect in the not-so-distant future.

And with all these advances in new sensor technology comes a new problem—how to manage the copious amounts of data that these sensors can generate. Eric Harclerode addresses this problem in his intelligence, surveillance, and reconnaissance (ISR) article, in which he discusses modeling intelligence processing, exploitation, and dissemination (PED) with a tool called the Fusion Oriented C4ISR Utility Simulation (FOCUS). FOCUS provides a new process for efficiently processing and analyzing large amounts of raw ISR data to ensure the data are both timely and actionable when reaching the intelligence community.

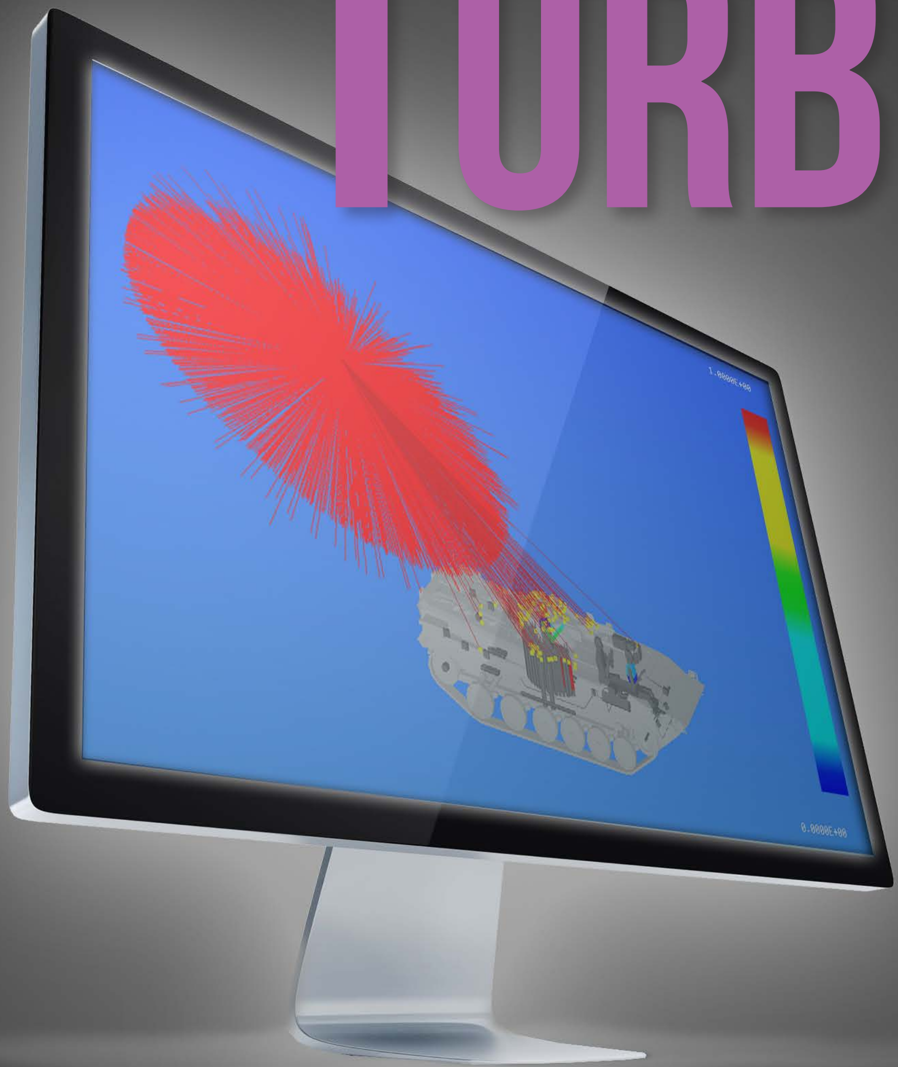
Authors Patrick Buckley and Scott Armistead discuss how an internal research and development (IR&D) project to investigate parallel processing, as applied to endgame codes, evolved and led to the development of a tool called TurboPK. As a traditional "point-burst" endgame code, TurboPK can be used to quickly simulate and analyze weapon kinetic energy and blast effects, including armor-piercing projectiles, fragments, exploding munitions, and air blast. This article discusses how weapons analysts can take full advantage of multi-core CPUs to increase M&S speed and reduce product development times.

John Farrier discusses how a decade's worth of modeling and simulation (M&S) growth and adaptation has been leveraged to give rise to a modern platform for simulation development, integration, and analysis. Built into applications spanning analysis, training, and intelligence, the Hybrid Integration and Visualization Engine (HIVE) is changing the way models and simulations are integrated within the Department of Defense (DoD). HIVE provides a core library with a large number of plugins, allowing the application of existing models and simulations to operate in an integrated environment while providing a reusable suite of simulation tools and visualizations. Thus, HIVE is proving itself to be an agile and capable tool for bringing down costs while promoting true model reuse.

Finally, in our Energetics article this quarter, Andy Taylor discusses the safety challenges of the energetics laboratory. For those engaged in the research and development (R&D) of new and novel energetic materials, there is a myriad of technical and safety challenges in the laboratory that need to be addressed and overcome. Whether it concerns the toxic precursors or the sensitivity of the synthesized energetic, the extremely volatile nature of energetics requires particular attention and vigilance. Taylor explains why energetic materials safety requires a multi-pronged approach that begins with defining the appropriate tasks to be performed and developing the respective project plan.

Looking ahead to our upcoming winter issue, the feature article will be discussing an innovative transportation concept called Hoverbike. The author will be providing a detailed description and several notional operational concepts of this incredible new technology. ■

TurboPK



AN ALL-INCLUSIVE, ULTRA-FAST VULNERABILITY AND LETHALITY ENDGAME CODE

By Patrick Buckley and Scott Armistead

INTRODUCTION

Parallel processing divides large problems into smaller problems that can be run simultaneously on multiple processors. Although the technique has been around for decades, it has largely been under the province of high-end scientific computing on supercomputers. But that situation has changed dramatically in recent years as commodity computer manufacturers have switched to multi-core central processing units (CPUs) that now offer four, six, eight, or more computing cores (as illustrated in Figure 1). Today, virtually every desktop, laptop, and notebook computer is built for parallel processing. That's the good news. The bad news is that most software is not designed for parallel processing, so the full power of these multi-core CPUs goes unused for many applications. Fortunately for weapons analysts, their principal simulation tool, endgame codes, are highly amenable to parallel processing and can take full advantage of multi-core CPUs to increase modeling and simulation (M&S) speed. Additionally, new capabilities that were not practically feasible before, such as near-real-time design optimization, can now be developed.

Admittedly, multi-core CPUs are not the only option for parallel processing. Multiple computers networked into a computing "cluster" are another option [1].

General-purpose computing on graphics processing units (GPGPU) is also receiving a great deal of attention [2]. However, the discussion for this article is limited to multi-core CPUs as one of the more affordable and easily implemented options that engineers and scientists have access to in their personal desktop and laptop computers.

TurboPK: A PARALLELIZED ENDGAME CODE PROJECT

In 2005, the authors of this article initiated an internal research and development (R&D) project to investigate parallel processing as applied to endgame codes, with a focus on ensuring traceability to Department of Defense (DoD) and industry standard methodologies and algorithms. That test bed has since evolved into a code called TurboPK. It is a traditional "point-burst" endgame code that runs on both Microsoft Windows and Linux platforms and can be used to simulate and analyze weapon kinetic energy and blast effects, including armor-piercing projectiles, fragments, exploding munitions, and air blast.

Unlike many legacy codes that generally only support a portion of the design optimization/vulnerability/lethality analysis, TurboPK is an all-inclusive munitions survivability and lethality engineering analysis and design code that supports design-to-P_K (probability of kill) requirements. It creates shotlines, traces shotlines through geometric models, applies penetration equations, computes damage probabilities to vulnerable objects encountered along shotlines, and applies fault tree analysis to vulnerable component damage probabilities. In doing so, it adheres to accepted standards for core endgame algorithms (i.e., penetration equations, component damage functions, fault tree analysis, and personnel casualty/incapacitation criteria). And like other endgame codes, TurboPK can analyze single shotlines, grids of parallel shotlines, single burst points, and sets of burst points. Because burst point set analysis is the most common use of the code, it is the primary focus of this article.

Through investigation and implementation of various parallelization schemes and employment of various software development tools, we were able to demonstrate that parallelizing endgame codes is practical in terms of providing impressive reductions in simulation run times and that these improvements scale linearly over a small number of cores.

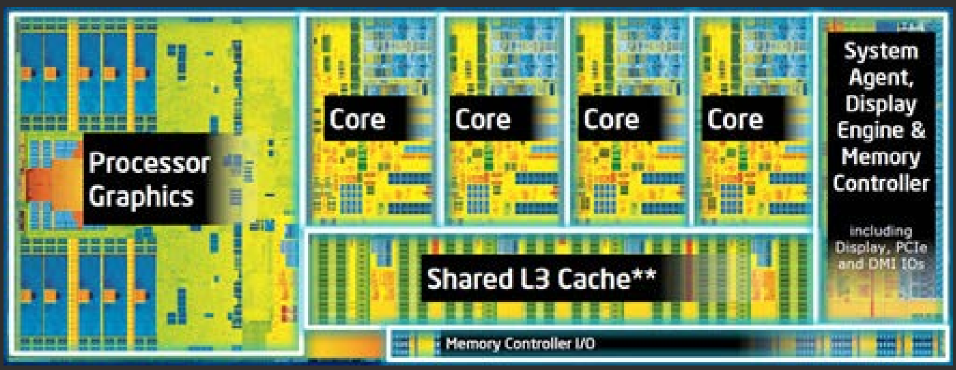


Figure 1: Typical Multi-Core CPU.

One obvious way to speed up the analysis of a set of burst points is to subdivide it into subsets that then run in parallel on multiple cores. The scheme employed in TurboPK is illustrated in Figure 2.

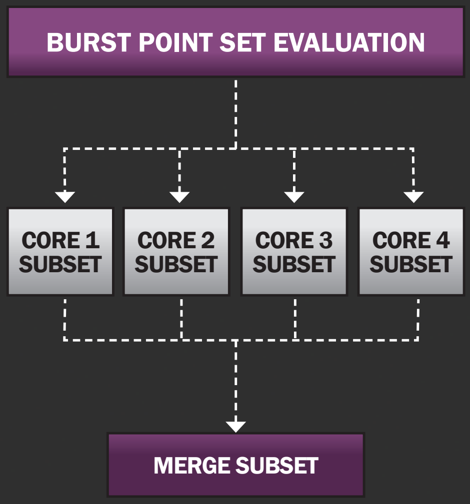


Figure 2: Typical Multi-Core Parallelization Scheme.

To implement this scheme, TurboPK creates a separate computational *thread* for each core, asks the operating system to launch the threads, waits for all the threads to complete their work, and then merges the results from all the threads. Each thread is a complete point-burst program. Point-burst simulations model a fragment warhead burst in Monte Carlo fashion as a set of fragment rays whose directions and speeds are randomized according to a prescribed distribution function. An example point-burst is depicted in Figure 3 as a set of fragment shotlines emanating from a point located a few meters above the target model of interest. In a point-burst code, each shotline is first ray traced against the target geometry model in question to determine which geometry objects, if any, it intersects.

The ray tracing step is computationally intensive and often consumes 80% of

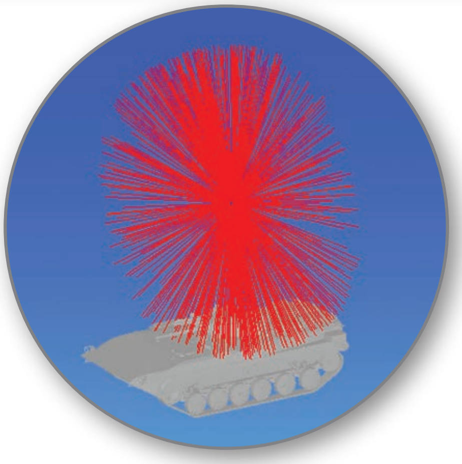


Figure 3: Example of a Warhead Point-Burst Simulation.

the runtime in a point-burst code due to the large number of potential ray-object intersection tests involved. Consider, for example, a warhead that ejects 2,000 fragments and a geometric model that has 100,000 triangles. In theory, that results in 200,000,000 ray-triangle intersection tests to be performed per point-burst calculation. Many such calculations are performed in a typical analysis session, so it is easy to see why ray tracing dominates the run time. Fortunately for endgame programmers, ray tracing has been the subject of a great deal of research, and there are numerous high-quality, open-source ray tracers that greatly reduce ray tracing times for endgame codes.

A number of ray tracers have been implemented in TurboPK over the years. The current default ray tracer is an open-source ray tracer called Embree [3], provided by Intel Corporation. Embree fits the scheme illustrated in Figure 2 because it is "thread safe." That is to say, the code manipulates only shared data structures in a manner that guarantees safe execution by multiple threads at the same time. Embree also employs a low-level type of parallelism in the form of Single Instruction Multiple Data (SIMD) instructions [2]. Among other things, SIMD enables Embree to test one ray against four triangles simultaneously. The result is the addition of a layer of low-level parallel processing to the high-level multi-core layer.

So how well does all of this parallel processing work? Let us consider an example burst point set calculation where the burst point set is a rectangle of burst points located at a fixed height-of-burst (HOB) relative to the target model (a typical simulation that might be run by legacy endgame codes). The exercise will be performed on a typical desktop computer with an Intel i7 four-core CPU. The target model is an aircraft model that has a set of vulnerable components (pilot, hydraulic lines, wire bundles, engine controls, etc.) typical of industry and DoD standard target geometric models (TGMs). The warhead ejects 2,000 fragments in a 20-degree side spray. Fragment mass is 240 grains each, and fragment ejection speed is 6,000 fps. The missile carrying the warhead is approaching in anti-parallel fashion (head-on approach direction). Warhead burst points are spaced 0.328 m apart in a rectangle

TurboPK is an all-inclusive munitions survivability and lethality engineering analysis and design code that supports design-to-Pk requirements.

measuring 30 m by 30 m. The HOB is 8 m above the bottom of the target geometry. At each burst location, 100 Monte Carlo point-burst calculations are performed, each of which results in a P_K value for the target of between 0 and 1 as a statistical indication of the likelihood of destroying or disabling the target in such a manner that it cannot perform its intended mission. Averaging the 100 individual point-burst P_K values yields a single-shot-average-P_K value for the burst point. Figure 4 illustrates the field of burst point markers color-coded by P_K (blue equaling a probability of 0 and red equaling 1).

There were 8,281 burst locations in this calculation, so there was a total

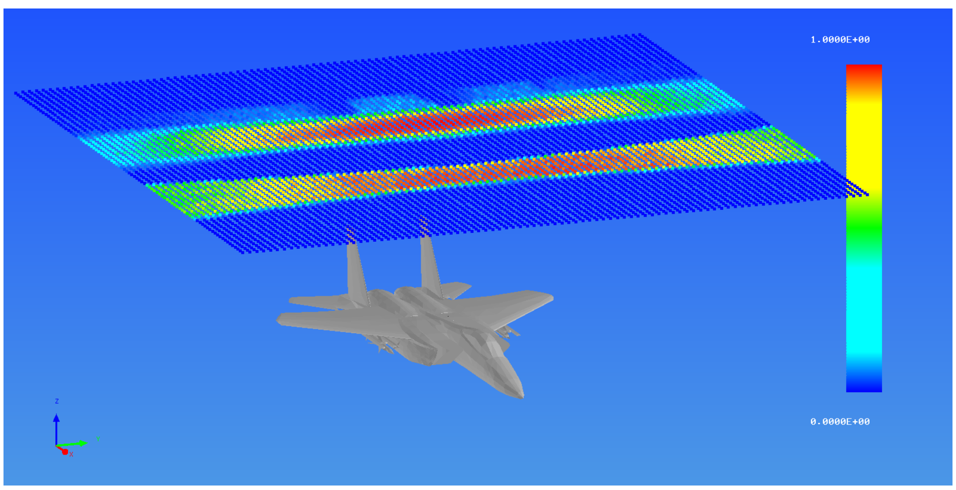


Figure 4: Example Burst Point Set Simulation and Display.

of 82,810 point-burst calculations. Each point-burst calculation involved 2,000 randomized fragment shotlines, so the total number of shotlines analyzed was 165,000,000. Averaged over all 8,281 burst points, the P_K is 0.25 for this example. To illustrate the value of parallelizing the calculations, the simulation was run on a single core and then on two, three, and four cores (as indicated in Figure 5).

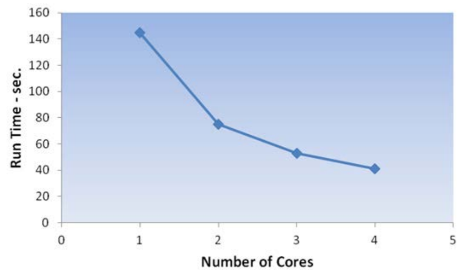


Figure 5. Simulation Results for Different Numbers of CPU Cores.

Run time for one core was 145 s and for four cores was 41 s, or a speedup factor of 3.54. That result is 88.4% of the theoretical maximum speedup factor of 4.0. Similar results have been demonstrated for other burst point set problems with different warheads types and configurations and different targets, including various ground vehicles, aircraft, and personnel. So it is safe to say that parallelizing endgame codes through multi-core computing is well worth the extra programming effort required.

> Ray tracing is computationally intensive and often consumes 80% of the runtime in a point-burst code.

INTERACTIVE WARHEAD DESIGN: A NONTRADITIONAL ENDGAME APPLICATION

As demonstrated in the previous section, fully parallelized endgame codes can do what legacy codes do now, but much faster. That fact alone is a significant benefit worth implementing. Such speed increases also allow endgame simulations to morph into new, nontraditional forms that can provide the end user with tools that were previously neither time- nor cost-effective to implement on a desktop computer. This section presents an example of incorporating warhead design *directly* into endgame simulation to support "design-to-P_K" requirements.

These days, warhead design is performed via highly sophisticated computational mechanics codes, such as the Combined Hydro and Radiation Transport Diffusion (CTH) [4] and LS-DYNA [5]. These codes are generally in the domain of experts and can provide highly accurate simulations of explosive-metal systems, but they are not typically considered to be fast-running. For some cases of interest, such as cylindrical-shaped fragmentation warheads, analytical approximations provide accurate first-order estimates of fragment ejection angles and speeds and also have the advantage of being fast-running (i.e., a few seconds) [6–8]. Because the authors have an interest in warhead design and endgame simulation, it was not difficult to extend the capability of the tool by adding warhead design directly into the TurboPK endgame simulation using the techniques described in Szmelter et al. [6], Charron [7], and Hennequin [8]. The idea is to enable a user-driven optimization loop. An optimization algorithm can also be added relatively easily (as illustrated in Figure 6), but currently the user steers all computations.

An interactive warhead design session starts by loading the target model elements (geometry model, damage

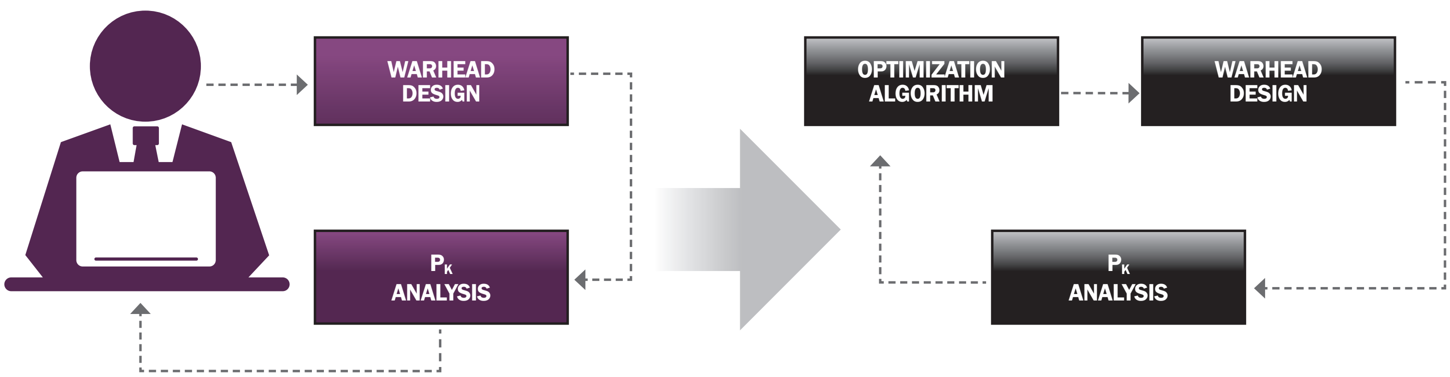


Figure 6: Addition of Optimization Algorithm.

functions, fault tree, etc.) and defining a set of burst points. The warhead design feature is accessed through the dialog box pictured in Figure 7. The warhead design described by the parameters in Figure 7 is a cylinder 10 inches long and 8 inches in diameter. The fragment case consists of cubes whose edge dimension is 0.375 inch. The total weight is 52.9 lbs, and the peak fragment speed is just above 6,000 fps (as indicated in Figure 8).

Figure 8 indicates the predicted fragment ejection velocity as a function of position along the fragment case. A similar prediction exists for fragment ejection angle. TurboPK integrates the velocity-angle profiles into a polar zone warhead description that defines a set of polar angle zones by the number of fragments in each zone and the fragment speeds at each zone boundary. That polar zone warhead description then becomes the active polar zone warhead for any subsequent point-burst calculations in TurboPK. This allows the user to go back and forth between warhead design and P_K calculation, all within the same computing session.

> TurboPK can simulate and analyze weapon kinetic energy and blast effects, including armor-piercing projectiles, fragments, exploding munitions, and air blast.

To illustrate the warhead design capability, let us consider an example calculation, performed on a typical desktop computer with an Intel i5 four-core CPU, involving a lightly armored vehicle. The burst point set involves a distribution of warhead burst points centered on the target origin. The burst point distribution is a Rayleigh distribution with a Circular Error Probable (CEP) of 2 m. The HOB is 3 m above the ground plane, the azimuth angle of approach (AoA) is 0 degrees (head on), and the elevation angle is 30 degrees from horizontal. In less than 3 s, 1,000 sample burst locations are generated and 20 Monte

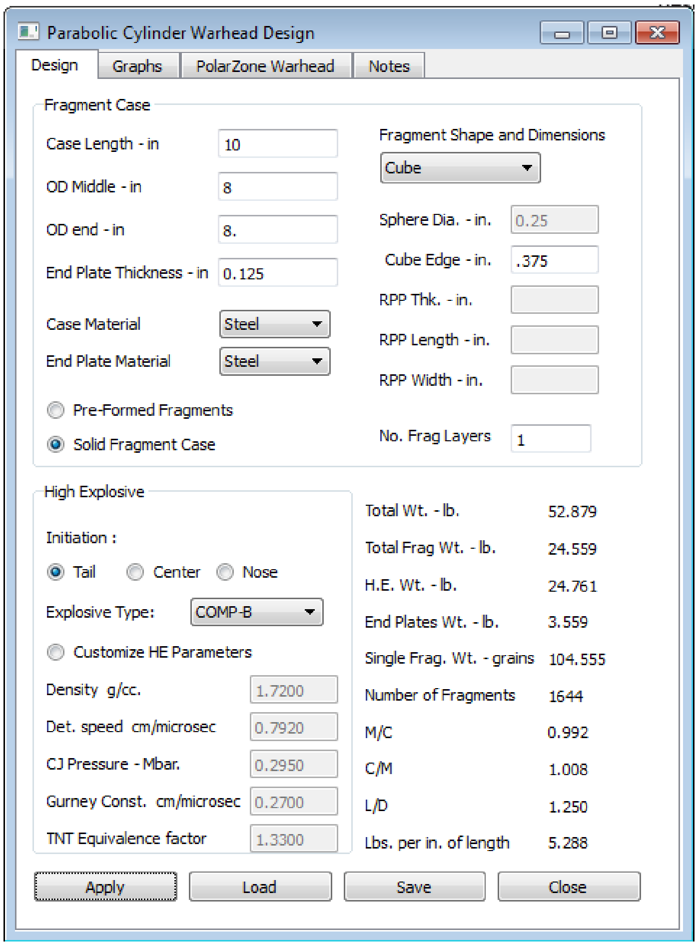


Figure 7: Warhead Design Dialog Box – Design Tab.

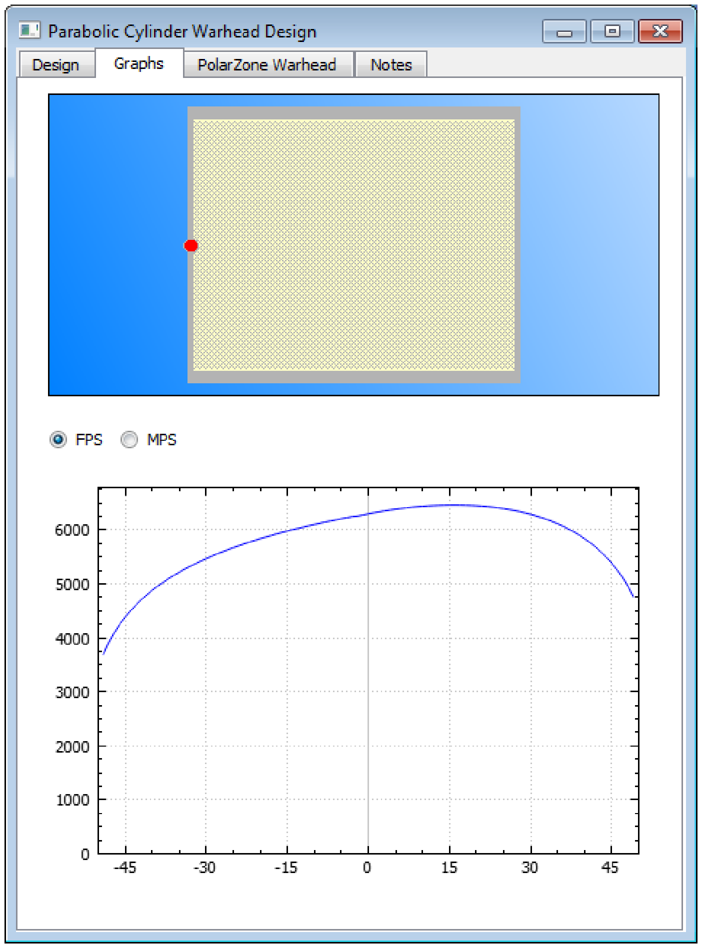


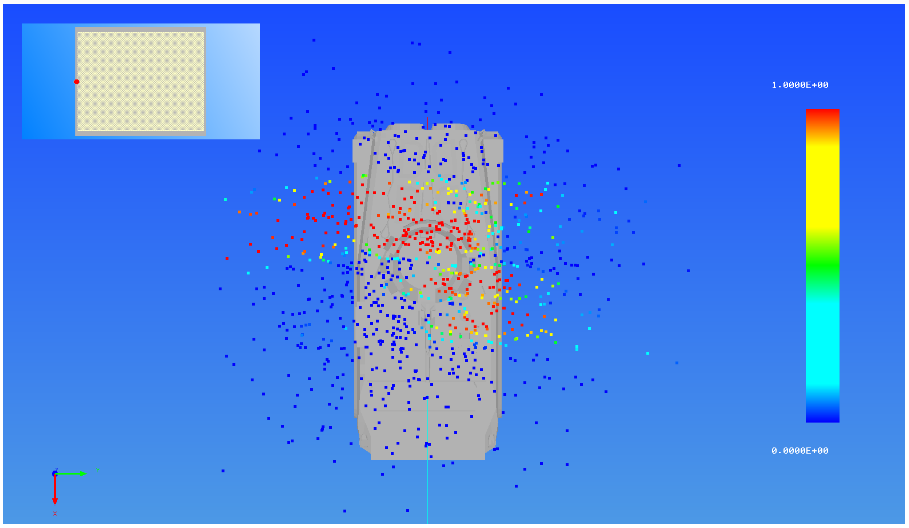
Figure 8: Warhead Design Dialog Box – Graphs Tab.

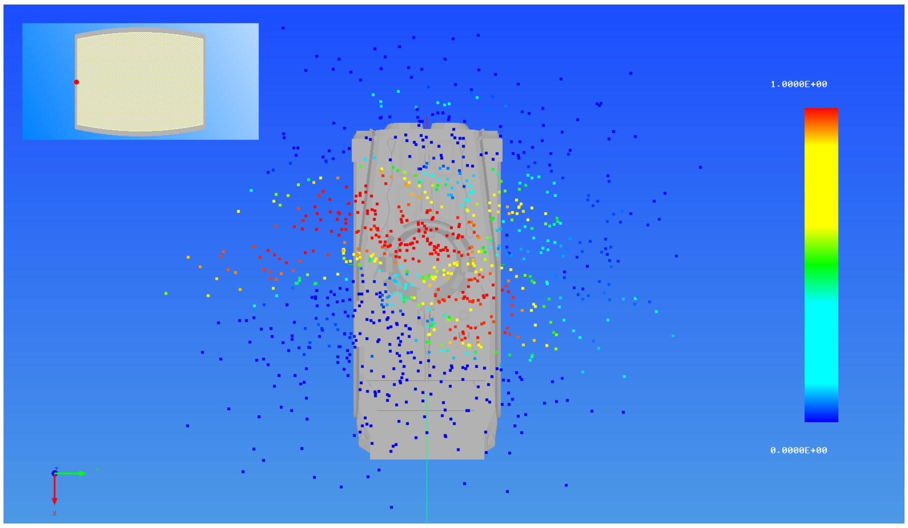
Carlo sample point-bursts are generated for each burst location, for a total of 20,000 sample point bursts.

Figure 9 illustrates a top view of the burst point markers color-coded by P_K for the baseline warhead (blue equaling a probability of 0 and red equaling 1). The inset in the upper left of the figure is a drawing of the warhead. The red dot indicates the detonator initiation (fuzing) location. The P_K averaged over all 1,000 sample burst locations is 0.32. Figure 10 illustrates the P_K markers for a slightly modified warhead, one for which the end diameter was reduced to 7 inches. Reducing the end diameter produces a slightly curved fragment case and reduces the weight to 48.9 lbs. Despite the reduced weight, the P_K *increases* to 0.394 due to the wider polar spray produced by the curved case. The total exercise from scenario setup to completion of both sets of simulation runs took less than 3 min.

Exploring a range of case thicknesses for the curved design and plotting the results in Excel take only a few additional minutes (in each case, the warhead length was adjusted to keep the total weight constant). The results indicate an optimum case thickness of around 7/16 inch (Figure 11), which may not have been obvious at the start. Nor was it obvious that a slightly curved case would have a higher P_K at lower weight than a straight cylinder.

While only five designs were evaluated in this admittedly small study, the results provide a warhead designer with valuable insights regarding fragment size and warhead geometry for a time investment of less than 15 min.





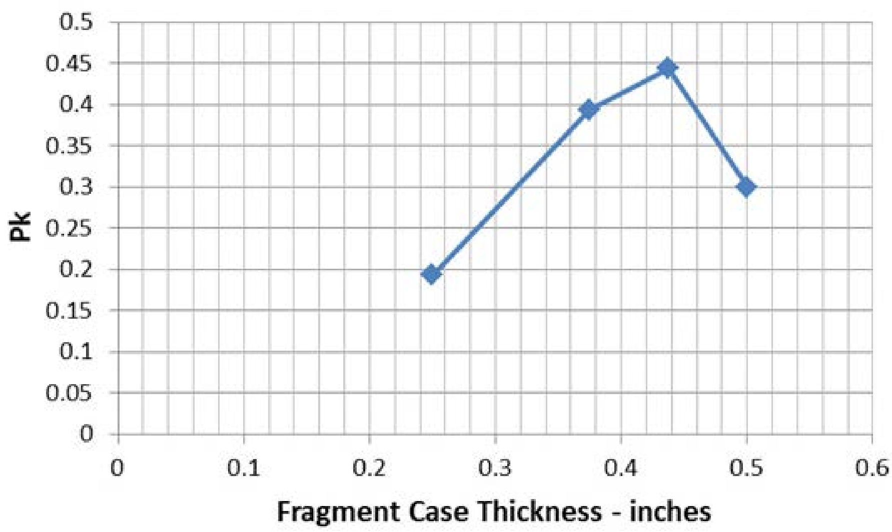


Figure 9 (top): Top View Burst Point Markers Over Target – Cylindrical Warhead Diameter of 8 inches.
Figure 10 (middle): Top View Burst Point Markers Over Target – Curved Warhead End Diameter of 7 inches.
Figure 11 (bottom): The Change in P_K by Case Thickness for the 7-inch Curved Warhead Example.

SUMMARY

Parallel processing has been demonstrated to work extremely well for traditional endgame codes. The primary payoff is substantial reduced processing time, even on commodity desktop machines. Moreover, this newfound computing power opens up the possibility of many new, nontraditional endgame applications, such as quick warhead design optimization at the desktop level (by, for example, embedding warhead design directly into an endgame simulation). Finally, given the relative ease and quickness with which the example analyses described herein were accomplished, a code of this nature also promises to make an ideal tool for rapid comparative studies and analysis-of-alternatives for warhead design considerations, optimization of weapon employment for a desired effect, weapon effectiveness studies, lethality analyses, and a host of other munitions-related efforts. ■

BIOGRAPHIES

PATRICK BUCKLEY is a senior scientist at the SURVICE Engineering Company's PMC Operation, where he develops software for weapon simulation and survivability/vulnerability analysis of kinetic and high-energy laser weapons (HEL). His 45-year career has included work in weapon testing and analysis and various software development projects for industry and academic research organizations. His current interests include novel applications of parallel processing methodologies and high-speed ray tracing software for HEL vulnerability assessments and fragmenting weapon optimization studies. Mr. Buckley holds a B.S. in physics and an M.S. in mathematics from the New Mexico Institute of Mining and Technology.

SCOTT ARMISTEAD is a DSIAC senior staff engineer as well as the SURVICE Engineering Company's Technical Operations Lead for its Gulf Coast Operation. He has more than 27 years of experience and is currently responsible for modeling, simulation, and analysis and computer engineering support for various customers. He is also experienced in infrared, visible, ultraviolet, millimeter-wave, seismic, magnetic, and acoustic sensors and weapons technologies; weapon systems effectiveness; countermeasures development; and platform susceptibility. Mr. Armistead holds a B.S. in nuclear engineering from the University of Florida.

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DTIC SEARCH TERMS:

Vulnerability Lethality Endgame Code

RESULTS: 2,830

- Military Operations, Strategy & Tactics (426)
- Vulnerability (309)
- Aircraft (264)
- Antimissile Defense Systems (248)
- Defense Systems (243)
- Survivability (242)
- Guided Missiles (236)
- Export Control (223)
- Computerized Simulation (197)
- Computer Programming & Software (194)

*See page 16 for explanation ▸

MODEL RELEASE - *Vulnerability Toolkit, Version 6.6*

On behalf of AFLCMC/EZJA, DSIAC is pleased to announce the release of the Vulnerability Toolkit, Version 6.6. This release includes the latest version of the Computation of Vulnerable Area Tool (COVART), in addition to a suite of other software tools beneficial to the vulnerability modeler. The most notable revisions include:

1. Updates to the FASTGEN ray tracing library, including the integration of the Spatially Enumerated Auxiliary Data Structure (SEADS) ray tracer and the restructuring of current capabilities to improve speed.
2. Updates to incendiary functioning calculations performed by ProjPen to account for obliquity effects.
3. A feature allowing the user to save component damage information and import it into a subsequent run.
4. Corrections to the ray-generation methodology used with proximity-burst threats to better account for fragment drag.
5. Resolution of 17 COVART software change requests.

The Vulnerability Toolkit is available through DSIAC at:

https://www.dsiac.org/resources/models_and_tools/vulnerability-toolkit

HIVE

AN INTEGRATING ENVIRONMENT FOR SIMULATION AND ANALYSIS

Figure 1: Visualization of an F-16 Engaged by Two Surface-to-Air Missiles (SAMs).

By John Farrier

INTRODUCTION

A decade of organic growth and adoption has given rise to a modern platform for simulation development, integration, and analysis. Built into applications spanning analysis, training, and intelligence, the Hybrid Integration and Visualization Engine (HIVE) stands ready to change the way models and simulations are integrated within the Department of Defense (DoD). HIVE is a Government-owned project purpose-built for enterprise integration of modeling and simulation (M&S) assets for training and analysis (as indicated in the screen shot in Figure 1). As a core library with a large number of available plugins, HIVE allows the application of existing models and simulations originating to new environments while providing a reusable suite of simulation tools and visualizations. The engine has found application to multiple simulation domains and levels of fidelity, proving it is an agile and capable project for bringing down costs while promoting true model reuse.

At its core, HIVE has the capability to collect thousands of measurements from its environment. It allows for analysis on these metrics and can rapidly generate information from a diverse range of integrated components. This integration brings disparate models and data sources seamlessly into a unified environment with infrastructure already in place to talk to a network, visualize output, collect statistics, generate reports, and drive other external hardware and software.

HIVE's integration capabilities bridge the gap between constructive and virtual simulations. As models are integrated within the engine as a plugin, the system matures a repository of objects and simulations, thus promoting true code reuse among integrated simulations. Each plugin then provides new functionality to existing applications without additional integration work. Integration with HIVE occurs with only minimal changes to an external model's original source code. HIVE makes it possible for analysts to simultaneously execute multiple models (even with different frame rates and fidelities) to produce an integrated simulation environment while maintaining each component's pedigree. For example, Figure 2 provides a notional visualization of a BlueMax aircraft acting as an airborne jammer, with the Enhanced Surface-to-Air Missile Simulation (ESAMS) driving a ground-based radar with antenna pattern and radar track cell, and with SHAZAM providing the endgame modeling. Data from all three of these models could be published over a Distributed Interactive Simulation (DIS) network.

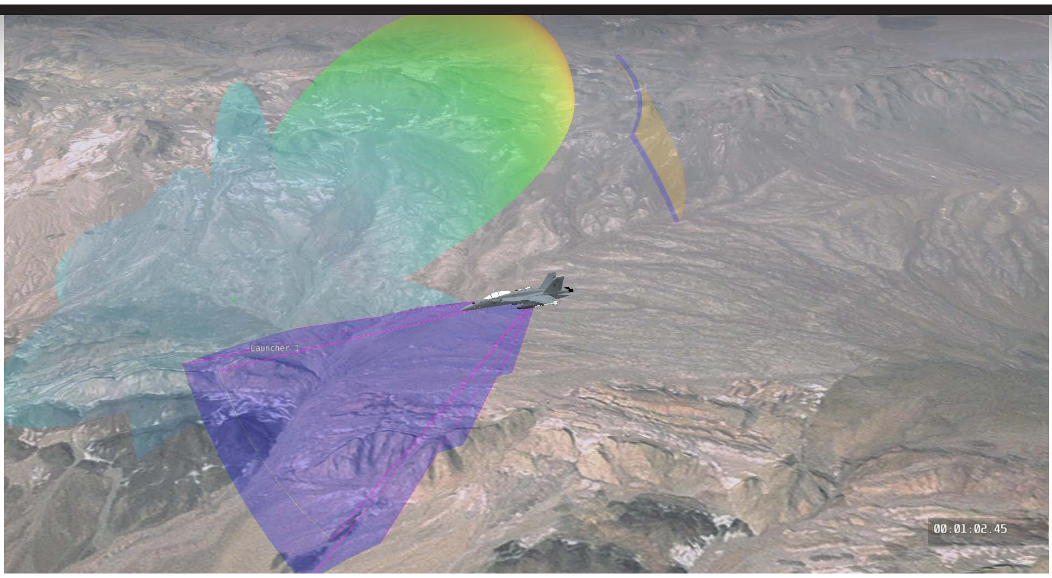

Figure 2. Multiple Model Execution in an Integrated Simulation Environment.

CROSS-DOMAIN APPLICATION

The motivation for the design and implementation of the HIVE M&S framework stems from the desire to bring together various phases of mission planning, execution, and analysis and their constituent tools.

> HIVE makes it possible to simultaneously execute multiple models (even with different frame rates and fidelities) to produce an integrated simulation environment.

Too often programs tend to do point integration, bringing in a model only into its environment with little formal testing. These stove-piped integrations cannot react to external software upgrades and offer little to no benefit to any other software project. One of HIVE's goals is to promote true software reuse; to provide correlation between the various tools, models, their inputs, and their outputs; and to foster rapid development of agile changes to mission configurations. As HIVE provides a common integration platform, individual models can maintain their own development processes and timelines. As models are upgraded, the corresponding HIVE plugin can be upgraded once, and all users of the plugin benefit. One simple illustration of this plugin component model is in HIVE data parsers. Table 1 illustrates many of the parsers available for different types of files within HIVE. Once a model is integrated into HIVE, it can immediately leverage all existing data file parsers.

HIVE has been used in a variety of applications including cockpit simulation; data visualization; test range integration; simulation development; intelligence, surveillance, and reconnaissance (ISR) sensor operator training (Figure 3); and operator ground stations. The engine is used extensively to federate simulations such as aero, weapons, and sensor models into a single cockpit capable of large-scale virtual simulation integration.

Table 1: Example of HIVE Plugins for Specialized File Input/Output

SIMULATION DATA FILES		2D & 3D MAP FILES		2D IMAGES		3D MODELS	
FORMAT	DESCRIPTION	FORMAT	DESCRIPTION	FORMAT	DESCRIPTION	FORMAT	DESCRIPTION
CPP	C++ Autocoder Output	ADRG	ADRG Raster Graphics	AVI	Windows Movie	3DC	3DC Point Cloud
DOT	Graphviz DOT	BLX	Magellan BLX Topo	BMP	Windows Bitmap	3DS	3D Studio
ESAMS	ESAMS Signatures	DDS	DirectDraw Surface	DDS	DirectX Image	AC3D	AC3D Modeler
ESAMS	ESAMS Antenna Patterns	DTED	Digital Terrain Elevation Data	GIF	GIF Image	BSP	Quake 3 BSP
F22	F-22 INS	EIR	Erdas Imagine Raw	HDR	High Dynamic Range	DAE	COLLADA 1.4x
GPS	NEMA GPS	FAST	EOSAT FAST	JPEG	JPEG Image	DXF	Autodesk DXF
HIVE	HIVE Binary Archive	GFF	Gsat File Format	PIC	PIC Image	FBX	Autodesk FBX
KBX	Nellis Keybox	GSAG	Golden Software ASCII Grid	PNG	Portable Network Graphics	IV	Open Inventor
MSN50	ICADS Mission 50	GTX	NOAA Vertical Dtatum Shift	RGB	SGI RGB Image	LWO	Lightwave 3D Object
MSNP5	ICADS Mission P5	IDA	Image Display and Analysis	RGBA	SGI RGBA Image	LWS	Lightwave 3D Scene
RCSAVE	FATS Signature	INGR	Intergraph Raster	TGA	Targa Image	OBJ	Alias Wavefront
XML	HIVE XML Inputs	MSGN	EUMETSAT Archive Native	TIFF	TIFF Image	OGR	Ogre
XML	BATS Signatures	SRTMHGT	SRTM HGT Format	XINE	XINE Image Stream	TXP	Terrapage Terrain
+5 More		+92 More		+6 More		+11 More	

Unmanned aerial vehicle (UAV) ground control stations and various operator interfaces have been developed with HIVE. In addition, custom hardware controls; aero, sensor, and weapons models; and HIVE-built optical sensor simulations have been merged into unified system simulations.

As HIVE integrates with hardware, Booz Allen Hamilton integrated an Oculus DK2 virtual reality headset into HIVE to create a man-portable air defense system (MANPADS) simulator. While the DK2 interface was new, existing components for flight dynamics, signatures, sensors, missiles, and endgame were used to provide simulator capable of an engineering-level assessment of a MANPADS with less than a week of development time.

SIMULATION FOR ANALYSIS AND DECISION-MAKING

The goal of M&S activities is ultimately to build knowledge. This knowledge is derived from data, which evolve into information, which evolves into knowledge through scientific analysis. With analysis as a goal, HIVE has a robust feature set for collecting and integrating data from all integrated components throughout a simulation's execution. The data can be formatted HIVE plugins and relayed directly to an analyst in a ready-to-use format. A primary goal of this work is to eliminate the continual development of small tools and macros that clutter the analysts' processes and tend to quickly become "dead code." As HIVE is designed to aid the analyst, it provides a rich set of tools to pull data directly from all integrated

Figure 3: A High-Fidelity ISR Training Simulator Developed Using HIVE for Project Liberty.

components, including via XML inputs, Python scripting, or plug-in development.

SECOND-ORDER EFFECTS

Integration of models with HIVE provides several second-order effects. The first is that the integration provides the integrated model with access to all other HIVE components and simulations that pertain to its domain. For instance, HIVE has a full-featured interface to BlueMax, a pseudo-6-degree-of-freedom (DoF) flight dynamics model. Any integrated model could use these BlueMax aircraft for a source of aircraft flight dynamics data, such as targets for a missile or a platform for carrying a sensor. Future integration of models and simulations will be accessible to all integrated components without having to develop a completely new interface to that specific component. This functionality helps to multiply the value of implementing a mature HIVE interface.

Another of these second-order effects is providing access to modern data visualization (Figure 4). HIVE visualization tools provide an automatic integration of existing displays to existing models, as well as the opportunity to create new displays for the model. HIVE allows users to integrate or create videos of the physical environment, user interfaces, complex data visualizations, or any custom display. The tool provides abstracted data visualization for any integrated component. Under the hood, it uses common tools and architectures for driving the graphics, which means that there is wide industry support and technical knowledge. Reuse of third-party libraries and graphics components is possible while ensuring that user development of new components can be readily accomplished without significant specialized HIVE-centric knowledge.

> HIVE allows its integrated models and simulations to work in constructive environments, virtual environments, and live environments all with the same toolset.

INTEGRATED LVC

The motivation to use Live, Virtual, and Constructive (LVC) simulations is found across the DoD. Running contrary to this approach is a significant library of models and simulations that were purpose-built to solve specific problems at various fidelities. HIVE allows its integrated models and simulations to work in constructive environments (e.g., doing Monte-Carlo simulations), virtual environments (e.g., interacting with users in real-time), and live environments (e.g., interacting with test range assets) all with the same toolset. This flexibility brings continuity and fidelity to acquisition, test, and training and provides for analogous comparisons across LVC domains using an identical tool set with identical data collection and analysis processes.

M&S SOFTWARE ENGINEERING

A dynamic build and distribution system allows for the size and complexity of a HIVE distribution to be tailored to its constituent model's needs. Specifically, a small nongraphical version of HIVE can be used to provide integration between

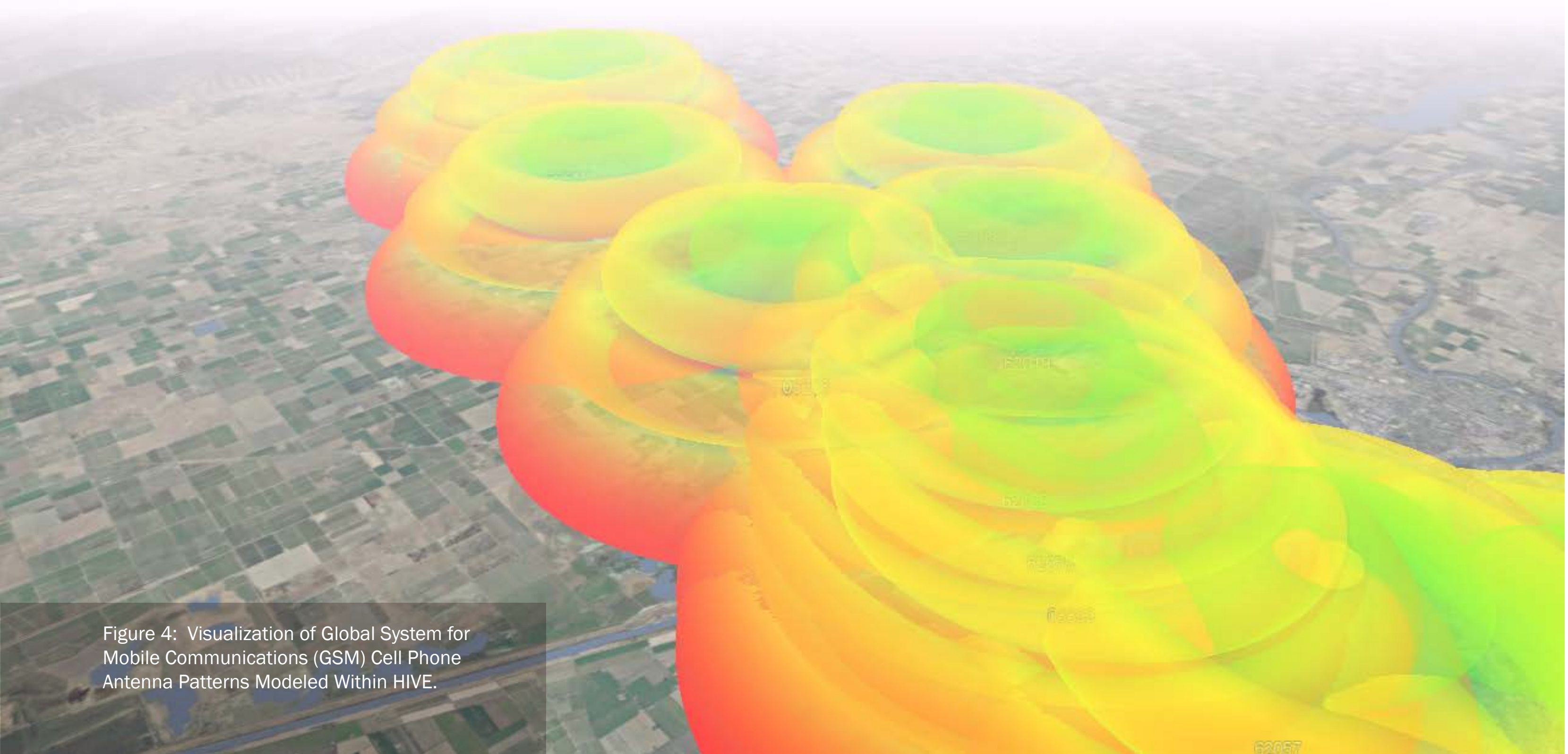

Figure 4: Visualization of Global System for Mobile Communications (GSM) Cell Phone Antenna Patterns Modeled Within HIVE.

two models without bringing along unnecessary plugins or dependencies.

The software itself is controlled in a modern continuous integration environment that includes detailed issue and bug tracking. Several different configurations of HIVE (e.g., 32-bit, 64-bit, with graphics, without graphics, Windows, Linux w/GCC, Linux w/Clang, etc.) are built and tested daily. Tests include regression testing, functional testing, and performance benchmarking. These processes aim toward allowing HIVE to be a stable, mature, and rapidly deployable solution to cross-platform simulation integration and visualization.

BLUEMAX VIRTUAL COCKPIT

For as long as HIVE has been in development, it has been providing a virtual cockpit for BlueMax. While HIVE's graphics engine provides out-the-window and heads-down displays, its integration engine has the most mature interface to BlueMax available. HIVE's test architecture has extensive integration tests within it for BlueMax which demonstrate perfect correlation between stand-alone BlueMax execution and defining scenarios within HIVE itself and running them within BlueMax, even for advanced waypoint and commanded control modes. Commonly used with a Thrustmaster Hands-On Throttle and Stick (HOTAS), the HIVE BlueMax cockpit (illustrated in Figure 5) supports multiple BlueMax players, multiple views of the scenario, and highly detailed data collection capabilities.

HIVE's mature and tested interface brings BlueMax's capabilities to all integrated HIVE components (such as ESAMS), providing an out-of-the-box high-fidelity target model capable of performing maneuvers with no additional integration effort required.

BRINGING HIGH-FIDELITY INTEGRATION TO THE JOINT ANTI-AIR MODEL (JAAM)

Starting in 2014, HIVE began to be integrated into JAAM to provide a link to ESAMS. ESAMS had long existed as a trusted model for high-fidelity SAM engagements, and HIVE had a mature interface to its capabilities. The idea was to use this existing, tested interface to provide ESAMS weapons to JAAM. Since this effort started, HIVE is now also providing access to the BlueMax6 pseudo-6-DoF aero-performance model. This is the first high-fidelity aero model integrated into JAAM and will be providing access to both domestic and foreign aircraft performance models in an upcoming release of JAAM.

Future efforts with this integrate may bring additional model integrations into HIVE that are used by JAAM. Such models include the Missile and Space Intelligence Center's (MSIC) Threat Modeling and Analysis Program (TMAP) models; Standard TMAP Interface and Model Structure (STIMS) and STIMS2 interfaces, air-to-air models, and air-to-surface models.

LIVE FROM THE NELLIS TEST AND TRAINING RANGE (NTTR)

Today, HIVE is tightly integrated with the NTTR, providing real-time kill removal and post-mission debriefing support for RED FLAG and other range activities. Working with the 507th Air Defense Aggressor Squadron (ADAS), HIVE was used to develop the Aggressor View application. Aggressor View provides a custom user interface on top of HIVE libraries (Figure 6) to access ESAMS. While ESAMS had traditionally been a constructive-only model employed by subject-matter experts, Aggressor View provides this high-fidelity capability to SAM assessors with little training required. Users have access to many advanced features within ESAMS, including its electronic attack (EA) capabilities. HIVE's internal type manager automatically selects the proper antenna patterns, target signatures, available EA techniques, and other parameters to construct the ESAMS engagement. Endgame analysis is currently being provided by SHAZAM. Again, HIVE is used here to build up the proper inputs and data files for SHAZAM and to visualize the fragment fly-outs at end game.

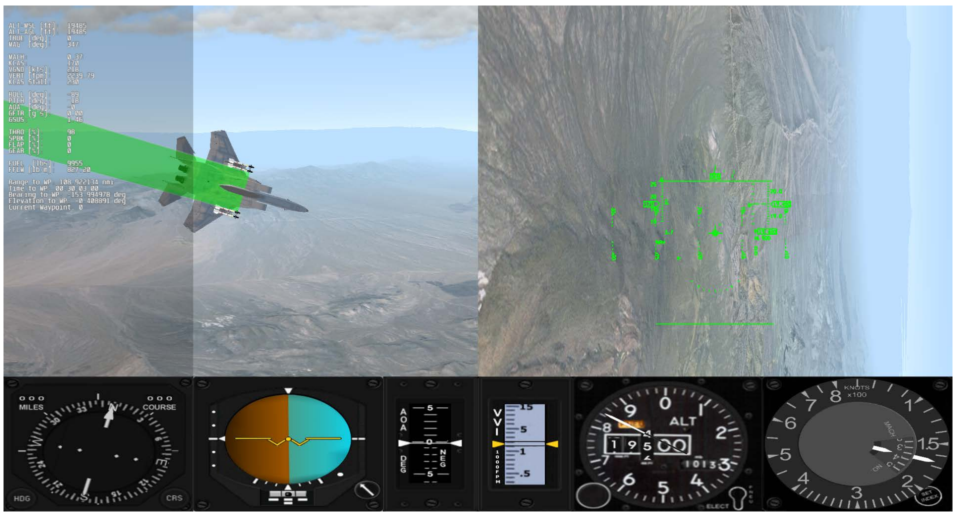

Figure 5: The Default BlueMax Cockpit in HIVE With Basic Flight Displays, a Heads-Up Display (HUD), and a Third-Person View of the Aircraft.

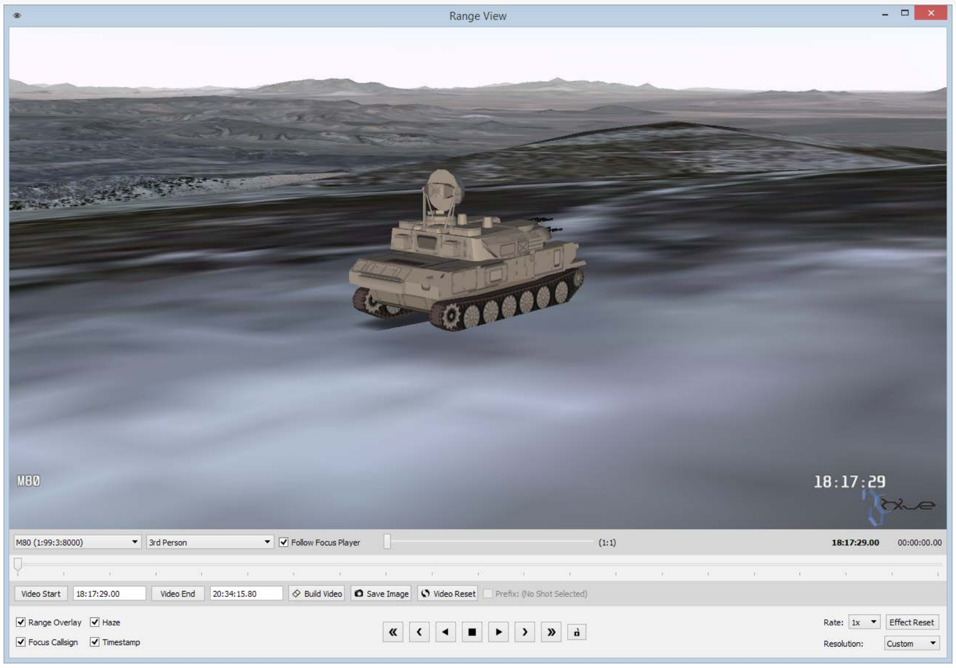

Figure 6: An Aggressor View Window, Showing a Real-Time Range View and Controls for Playback and Video and Image Capture.

Aggressor View, via HIVE, provides both real-time kill removal and highly detailed post-mission debriefing support. The 507th ADAS has successfully used Aggressor View for more than 7 years to enhance its ability to provide SAM training and support for the NTTR with high-fidelity, validated threat models. In the future, HIVE is anticipated to provide additional models, such as the MSIC TMAP models of SAM threats. Also expected is the near-term integration of Endgame Manager to replace SHAZAM for providing detailed endgame analysis of engagements.

HIVE's link to the NTTR's live and post-mission data can be made available to any HIVE-integrated model. This capability can be used to bring traditionally constructive models (such as ESAMS) into the LVC environment with little or no modifications required to the model itself.

HIVE GENERATION 8

The beginning of FY16 will see the release of HIVE generation 8. The latest generation of HIVE boasts an improved and simplified core application program interface (API), reduced internal complexity, improved performance, and a completely new graphics implementation. This version of HIVE will continue to support RED FLAG exercises, integrating simulations into JAAM and aiding in the reusable integration and visualization of simulations within the DoD. ■

BIOGRAPHY

JOHN FARRIER currently works for Booz Allen Hamilton. Mr. Farrier has approximately 20 years of experience in the design and development of software architectures, primarily for M&S systems, in support of the DoD and other agencies. Mr. Farrier is heavily involved in the C++ community through his work on open-source projects, on-line articles, and conference participation.

DTIC SEARCH TERMS:

Integrated Modeling Simulation Analysis

RESULTS: 142,000

- Computer Programming & Software (3,000+)
- Computerized Simulation (2,730+)
- Simulation (2,717+)
- Computer Programs (1,868+)
- Models (1,844+)
- Mathematical Models (1,762+)
- Symposia (1,713+)
- Electrical & Electronic Equipment (1,400+)
- SBIR (Small Business Innovation Research) (1,300+)
- Other (3,000+)

*See right for explanation ▸

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MODELING INTELLIGENCE PED WITH FOCUS

A TACTICAL-LEVEL ISR SIMULATION

By Eric Harclerode

INTRODUCTION

The increase in the use of intelligence, surveillance, and reconnaissance (ISR) systems over the past decade has created a significant increase of raw collection data available to the U.S. Army and intelligence community. Unfortunately, this surplus of data has also made it increasingly difficult to conduct efficient processing and analysis to produce timely combat information and actionable intelligence. Within the Army, this problem has sparked changes to intelligence-related force structure, development of new complex information systems, and other advancements, specifically in intelligence processing, exploitation, and dissemination (PED).

PED is a process that supports intelligence operations by converting and refining collected information for reporting to commanders, decision-makers, intelligence analysts, and other consumers through a collection of related functions [1]. The PED functions are crucial links between the collection asset and the information consumers in the continuous cycle to produce quality intelligence.

To meet the emerging needs of the Army and intelligence community, the U.S. Army Materiel Systems Analysis Activity (AMSAA) has initiated a PED modeling effort to increase the analytical capabilities of AMSAA's tactical-level ISR simulation, the Fusion Oriented Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) Utility Simulation (FOCUS). This article discusses the current state and future direction of PED, the scope and use of FOCUS, and the PED modeling development effort.

PED OVERVIEW

PED is the transformation of raw collected data into usable information distributed for further analysis and/or use as combat information by commanders and staff. When broken down, the PED process is a collection of functions that fit into one of the following categories:

- **Processing:** Automated or human cognitive-based conversion of collection data into useable information.
- **Exploitation:** The refinement of raw data to provide information by trained personnel or automation.
- **Dissemination:** The distribution or reporting of relevant information in a format suitable for commanders, staff, analysts, and other consumers [1].

PED is a critical component of the Army Intelligence Process, which supports commanders by providing intelligence needed to support mission command and the commander's situational understanding. As indicated in Figure 1,

Figure 1: The Army Intelligence Process.

the process consists of four steps (plan and direct, collect, produce, and disseminate) as well as two continuous activities (analyze and assess) [2].

The Intelligence Process is powered by the commander's Priority Intelligence Requirements (PIR) that are translated into a collection plan for the ISR assets. The assets collect raw data to satisfy the PIR; and the raw data are processed, exploited, and disseminated as usable information. The collection of information is continuously analyzed and assessed to produce intelligence and combat information to be disseminated to commanders and staff. Figure 2 illustrates the Intelligence Process as it flows from PIRs to actionable intelligence and the relationship to the Operations Process.

As PED becomes a growing concern to the Army, the military publications and doctrine that describe and define PED are continuously updated to reflect the current state of the rapidly evolving intelligence and PED enterprises. With the advancements in network technology, the intelligence enterprise is evolving from the traditional intelligence "stovepipes," where each intelligence domain (e.g., geospatial intelligence [GEOINT] and signals intelligence [SIGINT]) has a dedicated PED process, toward an integrated and distributed network. The distributed PED architecture will support multi-intelligence capabilities and provide continuous analysis with near-real-time collection asset tipping and cuing.

> PED functions are crucial links between the collection asset and the information consumers in the continuous cycle to produce quality intelligence.

FOCUS: A TACTICAL-LEVEL ISR SIMULATION

FOCUS is an AMSAA-developed, entity-level, event-driven, stochastic, ISR-centric simulation. It simulates ISR processes: sensor performance; tasking and collection; the exploitation and processing of data from all sources; the fusion of this information into tracks; and the communication of current predicted tracks to a visual simulation of entities and events in a three-dimensional (3-D) battle-space. FOCUS can be used to rapidly assess the performance of ISR systems in small, tactical-level vignettes in complex environments, such as urban and mountainous terrains. A typical use case is the comparison of a mix of aerial systems conducting searching and tracking missions using single or multi-INT sensors.

FOCUS represents entities at the platform (vehicle, aircraft, dismounted soldier, etc.) and sensor (electro-optical [EO]/infrared [IR], moving target indicator and synthetic aperture radars, SIGINT) levels. Behaviors such as movement, collection, acquisition, and communications are defined for each entity by the user when setting up

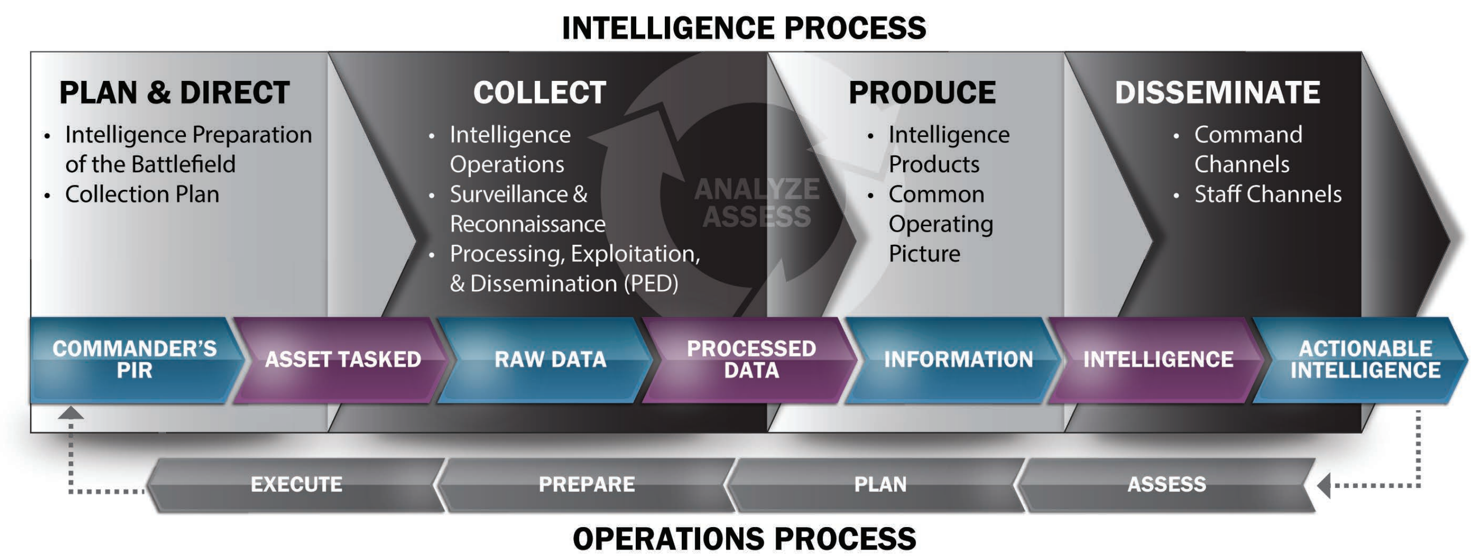


Figure 2: Intelligence Process and Operations.

the vignette. Behaviors can either be manually generated by placing waypoints on the terrain or by constructing a flow diagram of built-in, autonomous "missions" along with dynamic conditionals and events. Vignettes are built using an easy-to-use graphical user interface (GUI) that enables a user to quickly generate a scene, entities, and behaviors using point-and-click operations. FOCUS is capable of importing a variety of terrain formats, including both low (30–100-m interval) and high (1-m interval) resolution data. Buildings and other environmental features can be added to the terrain surface. A post-processing analysis toolkit is integrated into FOCUS to filter the output file and extract the desired results. The results can be viewed using the internal FOCUS graphs or exported for further spreadsheet analysis. Figure 3 provides a screenshot of FOCUS and sample results.

FOCUS includes the current sensor performance models. AMSAA is continuously improving the sensor representations and overall ISR process, including the ability to simulate Level 1 Fusion, the association of sensor measurements into tracks while maintaining fused position estimates, velocity estimates, and elliptical errors. Current applications of FOCUS include ISR sensor performance analysis; sensor coverage analysis; and tactics, techniques, and procedures (TTPs) comparative analysis.

A MODEL FOR ENABLING PED ANALYSIS

AMSAA's modeling approach for PED includes the potential impact and measures of effectiveness (MoEs) produced by the model. The overall objective of the PED modeling effort will focus on the following questions:

- *What are the key MoEs of a PED process implementation?* - The methodology must be able to produce metrics that measure the effectiveness of the PED process in the execution of the Intelligence Process.
- *What tradeoffs can be made in the PED implementation to influence the overall effectiveness of the PED process in the Intelligence Process?* - The methodology must allow tradeoffs of PED architecture attributes and enablers that will alter the measures of effectiveness for that PED implementation.

Impact

The addition of a PED modeling capability into a tactical-level ISR performance simulation, such as FOCUS, provides numerous benefits to Army and Joint analysis and modeling and simulation (M&S). In particular, adding this capability:

- Enables PED-related analysis to inform materiel acquisition decisions. The FOCUS PED implementation will allow AMSAA to analyze the effectiveness of PED implementations to meet operational requirements.
- Supports trade analysis of PED architecture materiel components/enablers. The FOCUS PED implementation will allow trade studies on the various materiel components and "enablers" of a PED architecture (e.g., network, storage, cloud infrastructure, processing capability, intelligence tools, and number/experience of analysts). Each component/enabler would have an effect on the throughput of the architecture and possible effects on quality of the intelligence. This could also include assessment of emerging PED technologies and algorithms.

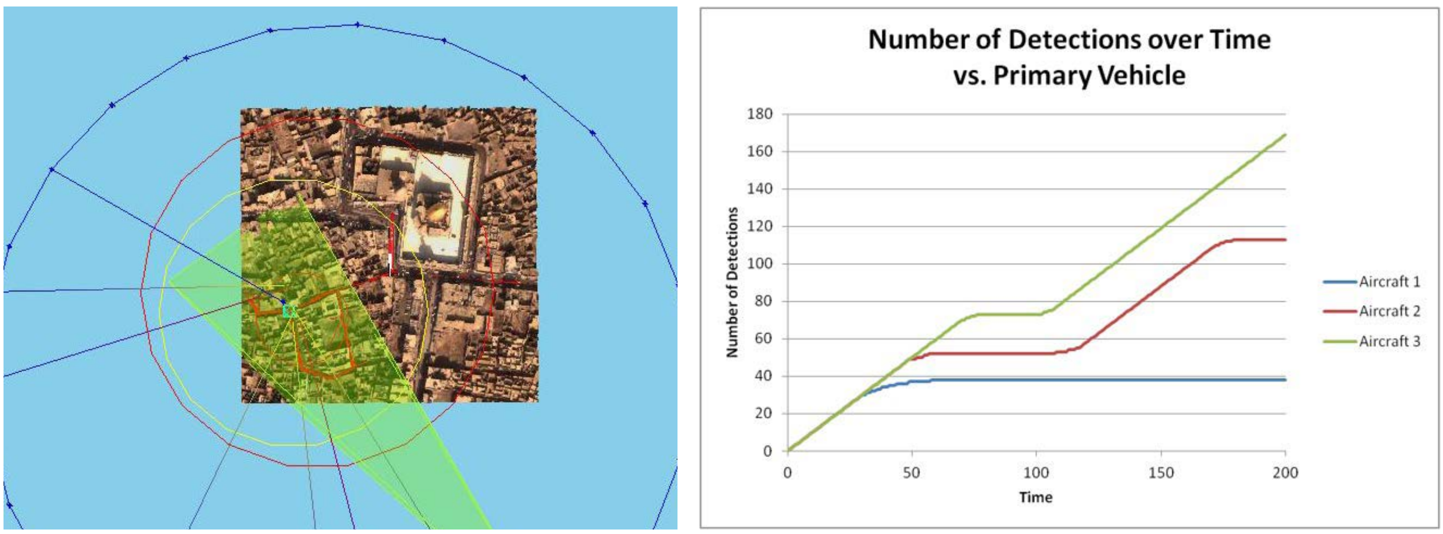


Figure 3: FOCUS Screenshot and Sample Results.

- Increases fidelity of ISR collection and tasking in current/future M&S. The FOCUS PED implementation will provide a more realistic depiction of information collection processes in M&S, which may significantly affect operational outcomes in scenario-based studies. Instead of scripted retasking of assets, dynamic tasking decision-making based on the results of the PED processes could occur.

PED MoEs

Metrics of a PED analysis capability will be realized as the modeling is tailored to meet the needs of the larger community. The following are potential MoEs:

- **Current Situational Understanding vs. Threat Ground Truth Ratio.** The intelligence collected over time creates a picture of the current threat for the commander. This MoE will provide a ratio of the number of threat entities acquired by the ISR systems vs. the ground truth number of threat entities over time. Variations of this MoE could incorporate the level of acquisition (e.g., detected, identified), a confidence in the threat location, and identification of high value targets.

FOCUS can be used to rapidly assess the performance of ISR systems in small, tactical-level vignettes in complex environments, such as urban and mountainous terrains.

- **Number of Intelligence Requirements Satisfied/Answered.** An Intelligence Requirement is information that is needed by a commander and staff to understand the adversary or other aspects of the operational environment. These requirements are defined as part of the plan and direct stage of the Intelligence Process and are answered through information collection. Given a set of Intelligence Requirements for a scenario, this MoE will provide the number of requirements answered over the course of the scenario, and with what confidence. Architecture tradeoffs could influence the time taken to answer the requirements.

Modeling Approach: PED Process Flow

As an expansion to FOCUS's existing tasking and collection capabilities, the PED model would be represented as a process flow that integrates the raw collection by an asset with the processing, exploitation, and dissemination elements of the PED function and that allows dynamic links to the mission command structure (asset tasking). The PED process flow is constructed using a collection of generic "building block" processes, each of which is intended to be extended to model the specific PED elements in a tactical-level scenario. Table 1 defines each of the initial PED blocks and gives examples of a potential concrete implementation.

Most of the new functionality within FOCUS and system trade-offs will

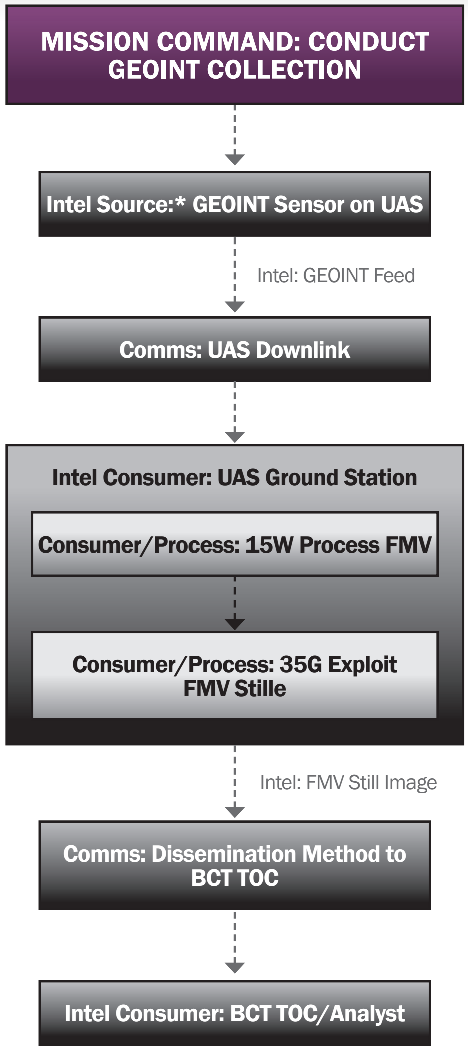
Table 1: PED Process Flow Blocks

PED "BUILDING BLOCK"	DEFINITION	EXAMPLES
Source	An object that is capable of creating a piece of information/intel	GEOINT sensor, SIGINT sensor, human intelligence (HUMINT) collector, historical database
Intel Type	An information/intelligence item	Raw sensor feed, video, intel reports, products
Process	A process that can manipulate the information/intelligence or perform some function as part of the architecture	Automated processing, human analyst imagery exploitation, data fusion
Consumer	An object that is capable of receiving, performing processes or holding information/intelligence data	PED node, commander, database
Communications	A process that transfers information/intelligence from a source to a consumer	Unmanned aerial system downlink, email, chat
Conditional Filters	A conditional test to allow for dynamic threads through the architecture based on the vignette state	Intelligence requirement met/not met, high-value individual (HVI) tracked
Mission Command Link	A link that activates the Mission Command Process Flow to dynamically change the maneuver or collection plan	Maneuver to area of interest, track HVI

occur in the Process flow blocks by modeling complex processes and system capabilities. Potential Process flow blocks include the following:

- ***Information Systems*** – a system designed for managing, pushing, or broadcasting information/intelligence for a variety of recipients; these systems may also have tools that support the entire Intelligence Process.
- ***Human-Systems Integration*** – human-based processes are heavily dependent on the workload and experience of operators/analysts and have effects on the timeliness and quality of the information/intelligence produced. Most sensor data are processed and exploited by a human at some point during the PED function.
- ***Applications/Tools*** – tools for processing/exploiting using thin client or thick client tools.
- ***Data Fusion*** – correlating and performing state estimation of target detection data to form tracks (i.e., Level 1 Data Fusion, a current FOCUS capability), aggregating multiple objects to identify groups/units (i.e., Level 2 Data Fusion, future capability).

Figure 4 illustrates a notional PED process flow, from the ISR collection asset through a consumer via a communications system to a commander. The commander can then dynamically retask the ISR collection systems. The final methodology would allow multiple layers of this process using varying combinations of ISR systems, communications systems, PED nodes, and commanders. The process would allow insertion of additional processes into the flow as more complex procedures are developed.



**Sensor continuously feeds Intel into process flow based on acquisition timeline.*

Figure 4: Notional PED Process Thread.

CONCLUSION

PED analysis has quickly emerged as a critical component of any analytical study of ISR systems. AMSAA is preparing for the future analysis needs of the Army and Joint intelligence communities by developing a PED modeling capability within FOCUS. Through the use of this tool and the evolving PED implementation, a new capability is being developed to model the Intelligence Process with high fidelity, enabling trade space analysis of PED-related systems and processes. ■

BIOGRAPHY

ERIC HARCLERODE currently works as an operations research analyst with the U.S. Army Materiel Systems Analysis Activity (AMSAA), working in the area of intelligence, surveillance, and reconnaissance (ISR). He is the lead developer of the Fusion Oriented Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) Utility Simulation (FOCUS), having developed and executed the simulation for use in Joint and Army analytical studies, including the Aerial Reconnaissance and Surveillance Portfolio Analysis and the Joint Cooperative Target Identification - Ground – Fire on Dismounts Analysis. Mr. Harclerode has a B.A. in mathematics and computer science from McDaniel College and an M.S. in computer science from The Johns Hopkins University.

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[2] Headquarters, Department of the Army. "ADRP 2-0 Intelligence." August 2012.

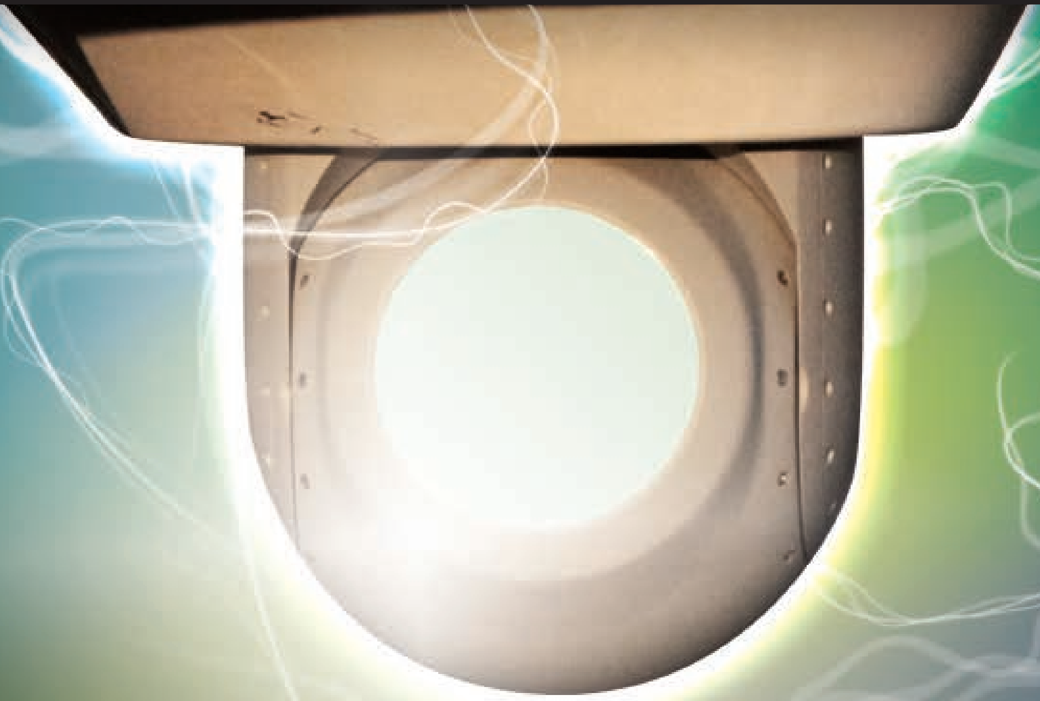
DTIC SEARCH TERMS:

ISR Modeling

RESULTS: 29,700

- Military Operations, Strategy & Tactics (2,978)
- Computer Programming & Software (2,345)
- Theses (1,814)
- Military Intelligence (1,749)
- SBIR (Small Business Innovation Research) (1,688)
- Military Forces & Organizations (1,558)
- SBIR Reports (1,508)
- Computer Programs (1,483)
- Symposia (1,479)
- Algorithms (1,393)

*See page 16 for explanation ▸



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THE HISTORY, TRENDS, AND FUTURE OF INFRARED TECHNOLOGY

By James Teague and David Schmieder

INTRODUCTION

Infrared (IR) technology has undergone a remarkable transformation over the last century. Rooted in 19th and 20th century developments in photometry, colorimetry, and radiometry and then driven by the military's ongoing desire to "own the night," IR technology now plays a critical role in U.S. defense capability, as it provides our combat personnel with the "eyes" to see and target our adversaries both in daylight and darkness. As with any historical development, the path leading up to today's IR technology holds important lessons for the path leading toward tomorrow's. Perhaps even more important are the transformative capabilities and trends that are currently emerging and that will shed light on what will likely be even more transformative capabilities in the future. Accordingly, this article provides a brief history of IR sensors and systems, as well as current trends and future projections for this important technology.

HISTORICAL PERSPECTIVE

World War II was the motivation for the development of the first practical, though crude, IR imaging devices [1]. These devices fell into the two categories: (1) viewers that used ambient light-amplifying image converter tubes, and (2) devices that we refer to today as IR Search and Track (IRST) systems. Interestingly, while precision-guided munitions were developed and used in World War II, IR variants were not developed in time to be used in combat. However, image converter tubes were used in combat by the United States, Germany, and Russia and therefore were of greater interest. These converter tubes used a photoemissive detector that was only capable of responding to about 1.3 μm [2] and not capable of seeing object self-emissions. In principle, they could see and amplify ambient light at night, such as starlight. In practice, however, their sensitivity was so poor that they almost always had to be paired with a covert source of artificial IR illumination, such as a searchlight, with a visible light blocking filter. Their main application was for rifle/sniper scopes, as pictured in Figure 1. These image converter tubes were the forerunner of what are today called image intensifiers. Modern image intensifiers are sufficiently compact to be used in goggles and are sensitive enough to see reflected ambient light without the need for artificial illumination.

The development of IR imaging devices has always depended on the availability of suitable detectors. From that standpoint, the Germans developed a type of detector that had the most importance for modern IR systems. In 1933, Edgar Kutzscher [3] at the University of Berlin discovered that lead sulfide (PbS) could be made into a photoconducting detector. Lead sulfide photoconductors had the advantage of being able to respond to longer IR wavelengths (e.g., out to 2.5 μm) so they could detect self-emissions from hot objects, such as engine exhaust pipes and ship stacks. When coupled with optics, scanners, and a cathode ray tube for display, these photoconductors were made into IRST systems, although they were not called by that name at the time. Prototypes were tested on German night fighter aircraft for the detection and tracking of Allied bombers as well as on shore to detect ships in the English Channel. The detectors were sufficiently mature to be transitioned to relatively high-volume production, but the war ended before systems using them could be manufactured.

After the war, Kutzscher immigrated to the United States and assisted with the transfer of PbS technology. This transfer ushered in the beginning of a slow but ultimately productive domestic detector development process. Greater sensitivity was needed, and this sensitivity could most directly be provided by developing detectors that responded in the 8–12-μm-long wavelength IR (LWIR) band. The LWIR band is a highly desired operating band because it provides the most signal for a given difference in temperature between an object and its background (e.g., when imaging terrestrial objects). Unfortunately, that band is also one of the most difficult for detectors to work in because long-wavelength photons have lower energy than short-wavelength photons. So detecting LWIR photons also means detecting other low-energy products, such as latent heat-generated dark current and its associated noise. The first practical LWIR detector material discovered was mercury-doped germanium (Hg:Ge), but it had to be cooled to 30 K with large, heavy, and expensive multistage cryocoolers to mitigate the dark current. Nevertheless, systems equipped with Hg:Ge detectors demonstrated a significant increase in sensitivity.

The technology lingered until 1959 when W. D. Lawson [3] of the U.K. Royal Radar Establishment, Malvern, discovered benefits of the alloy Mercury Cadmium Telluride (HgCdTe or MCT). This innovative material could detect LWIR radiation at the significantly higher temperature of 80 K because of lower dark current. The result was a dramatic decrease in cryocooler size, weight, and cost, with similar dramatic decreases in the respective support equipment. The weight of some systems, for example, was reduced from 600 lbs to less than 200 lbs, although some of that weight reduction can be attributed to the detectors also being made smaller.

Figure 1: 1940s U.S. Army Sniper Scope (U.S. Army Photo).

According to Lucian "Luc" Biberman [4], a keen-eyed witness in the early 1950s and co-developer of the Sidewinder IR missile seeker, the principal hardware focus of that era was on simple radiometric instruments and air-to-air missile seekers. This focus resulted in the highly successful Sidewinder missile, which was largely the beneficiary of uncooled PbS detector technology. But perhaps more importantly, it led to organized methods to share information in the fledgling community of interest. First came the government-industry co-sponsored Guided Missile IR Conference (GMIR). That information-sharing, in turn, led to the establishment of the Infrared Information Symposium (IRIS)

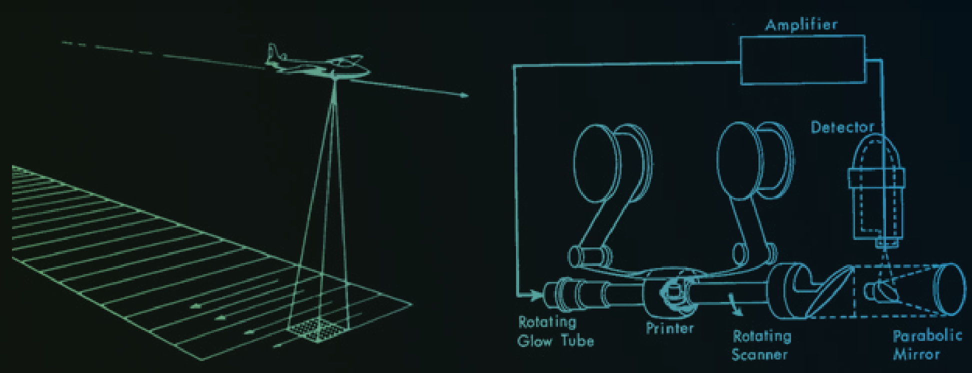

Figure 2: Illustration of an IR Mapper, Where an Image Scanned by a Rotating Mirror Is Transferred to Film via a Synchronously Scanning Glow Tube Modulated by the IR Detector Output. The Aircraft's Forward Motion Adds the Second Dimension to the Raster Scan [5, 6].

in 1956, which later became known as the Military Sensing Symposium (MSS). The MSS continues today in its extended charter to hold meetings and publish proceedings as a way to foster IR information exchange. The symposium is widely regarded in the community as an indispensable tool for workers in the field to stay abreast of important programs, technological advances, and marketing opportunities.

Developers, of course, walk a fine line between wanting to get their products exposed while simultaneously wanting to avoid giving away too much information to their competitors. However, most participants in government and industry agree that they all have more to gain than to lose from this forum, which is now nearing its 60th anniversary. Arguably, the military users have had the most to gain, as they have leveraged this forum to describe their needs, as well as the effectiveness of products they have tested and fielded. Thus, one import by-product of the MSS has been the creation of healthy competition to develop and field better solutions for the military user.

In the 1960s, the Vietnam War continued to have a major impact on IR imaging system development. The need to interdict supplies and troops infiltrating down the Ho Chi Minh Trail at night to avoid detection was a high priority. Early systems were relatively crude IR mappers, which initially were single detectors that were swiped one scan line at a time across the ground with a scan mirror. The signal output was fed into a glow bulb illuminating a spot on a photographic film carriage. The forward motion of the aircraft resulted in successive scan lines being imposed on a film strip fed by a reel that was synchronized to the speed of the aircraft (as illustrated in Figure 2).
At the time, these systems were highly successful for reconnaissance but not much use for providing direct fire support. Nevertheless, they demonstrated the utility of IR imaging and soon led to directable real-time imaging systems, which we now call Forward-Looking IR (FLIR) systems.

The curious name of FLIR was derived from the first directable sensors adding a vertical scan mirror so the detectors could be scanned in two directions. This feature enabled the system to look forward instead of down. Moreover, the resulting signal was fed through a scan converter so it could then be viewed in real time on a standard cathode ray tube. This development was a major advance, and systems were soon integrated into pod-like targeting systems that are still in use today on fighter bombers, gunships, and drones.

In the late 1960s and early 1970s, efforts were made to standardize IR technology to reduce cost and improve reliability. The resulting devices were referred to as "first generation" items. Accordingly, first-generation linear arrays of intrinsic MCT photoconductive (PC) detectors were developed that responded in the LWIR band. All services were required to adopt the standard "common module" building blocks pioneered by Texas Instruments and developed under Army supervision. Standardization and improved detectors facilitated high-volume production and dramatic cost reductions. As a result, the 1970s witnessed a mushrooming of IR applications. IR systems were mounted on all manner of platforms, ranging from ground armor, including tanks and armored personnel carriers, to aircraft and ships.

During this era, most of the world's advanced militaries had image intensifiers, but their use required ambient illumination and a clear atmosphere. In overcast or smoke and dust conditions, image intensifiers were effectively blind. Nonetheless, the Army's capability was effectively expanded from day warfare to day and night warfare. The Army's motto became "we own the night," and indeed it did. The FLIR systems built in this era from standardized components were later referred to as generation 1 or simply "Gen 1" systems.

The invention of charge transfer devices such as charge coupled devices (CCDs) and complementary metal-oxide-semiconductor (CMOS) switches in the late 1960s was another major breakthrough that led to the next generation of FLIRs. Detector arrays could now be coupled with on-focal-plane electronic analog signal readouts, which could multiplex the signal from a large array of detectors. These multiplexers were called readout integrated circuits (ROICs). They made it possible to eliminate the need for a separate dedicated wire to address each detector as well as the need for each detector to have its own dedicated amplifier circuit. They essentially decoupled the number of wires needed from the number of detectors used. This breakthrough enabled the fabrication of high-density arrays, which increased sensitivity and permitted building large arrays. Now, scanning line arrays with many columns and staring focal plane arrays (FPAs) were, in principle, no longer limited by the number of wires, preamplifiers, post amplifiers, etc., that could be packaged in a practical size.

FLIRs that used this advance technology were referred to as "Gen 2" (although the Army used the term only for its scanned FPA approach). And of course, integrating Gen 2 detectors to readout electronics was not straightforward. Early assessments of this concept showed that photovoltaic (PV) detectors made from InSb, PtSi, and HgCdTe detectors were essential because their high impedances were crucial for interfacing with the readout multiplexers. Alternatively, lower impedance detectors would have drawn more current and power, which would have heated the focal plane and required correspondingly higher power and larger cryocoolers.

While HgCdTe PC detectors were the workhorses of Gen 1 FLIRs, it was not easy to make them work as PV devices. PV detectors require a delicate pn junction, which is much more susceptible to material defects and dark current. Nevertheless, the material itself had other qualities few other materials could match, such as a narrow bandgap with low dark current, which allowed it to be operated at 80 K in the LWIR band, the highly desired band for ground combat. Accordingly, in the late 1970s through the 1980s, MCT technology efforts focused almost exclusively on PV-device configurations.

This effort paid off in the 1990s with the birth of second-generation IR detectors, which provided large two-dimensional (2-D) scanning arrays for the Army. And by this time, the Air Force and the Navy were no longer constrained to adopt the Army's standard. Subsequently, these Services developed staring arrays around InSb, which were less expensive, responded in the 3–5-μm band, and were better suited to their operating environment.

The 1990s also saw both military and civilian applications of IR technology receive a boost in interest when room temperature thermal detectors were perfected in the form of staring focal plane arrays. Recall that thermal detectors differ from the photon detectors described previously in that thermal detectors act like tiny

1835
First Termopile IR Detector
Macedonio Melloni makes first thermopile IR detector.

1860
Blackbody Theorem
Gustav Kirchhoff formulates teh blackbody theorem E=J(T,n).

1873
Discovery of the Photoconductivity of Selenium
Willoughby Smith discovers the photoconductivity of selenium.

1879
Stefan-Boltzmann Law
Stefan-Boltzmann law formulated empirically that the power radiated by a blackbody is proportional to T4.

1880s
UV Catastrophe & Infrared Catastrophe
During the 1880s and 1890s Lord Rayleigh and Wilhelm Wien both solve part of the blackbody equation, but both solutions are approximations that "blow up" out of their useful ranges. This problem was called the "UV Catastrophe and Infrared Catastrophe."

1901
The Blackbody Equation & Theorem
Max Planck published the blackbody equation and theorem. He solved the problem by quantizing theallowable energy transitions.

1905
Theory of the Photoelectric Effect
Albert Einstein develops the theory of the photoelectric effect, determining the photon. Also William Coblentz in the spectroscopy and radiometry.

1917
Development of theThallous Sulfide Detector
Theodore Case develops thallous sulfide detector; British develop the first infrared search and track (IRST) in World War I and detect aircraft at a range of one mile (1.6 km).

1935
Lead Salts
Early missile guidance in World War II.

1938
Pyroelectric Effect Prediction
Teau Ta predicted that pyroelectric effect could be used to detect infrared radiation.

1945
The Zielgerät 1229 "Vampir" Infrared Weapon System Introduced
The Zielgerät 1229 "Vampir" infrared weapon system is introduced as the first portable infrared device to be used in a military application.

1950s
Infrared Images Formed
Paul Kruse (at Honeywell) and Texas Instruments form infrared images before 1955.

1950s
Nomenclature & Radiometric Units Defined
During the 1950s and 1960s nomenclature and radiometric units were defined by Fred Nicodemenus, G.J. Zissis and R. Clark, Jones defines D*.

1952
Discovery of InSb
H. Welker discovers InSb.

thermometers and exhibit a change of temperature, which is then sensed. Generally, these detectors are much less sensitive than cooled photon detectors, but when large numbers are used in a staring focal plane array, they become sensitive enough to be used in important roles in driver's night viewers, rifle scopes, and missile seekers. That ability, combined with their low cost, low power, and room temperature operation, made them extremely attractive.

In 1994, Honeywell patented a microbolometer thermal detection approach using vanadium oxide (VOx) that was developed under the government's HIgh-Density Array Development (HIDAD) program. The patent was subsequently licensed to many other U.S. aerospace companies and to some foreign countries under rigid export control restrictions.

In addition, developments in FPA technology have revolutionized IR imaging. Progress in integrated circuit design and fabrication techniques has resulted in continued rapid growth in the size and performance of these solid-state arrays. The timeline illustrated in Figure 3 lists some significant events in the history of U.S. IR technology development leading up to the early 2000s.

- **1800:** Sir William Herschel, an astronomer, discovered IR.
- **1950–1960:** Single-element detectors first produced line scan images of scenes.
- **1970:** Philips and English Electronic Valve (EEV) developed Pyro-Electric tubes. The English Royal Navy used the first naval thermal imager for shipboard firefighting.
- **Mid-1970s:** MCT technology efforts focused on Common Module (Gen 1) devices.
- **1970s–1980s:** MCT and InSb technology efforts focused on PV and producibility of devices.
- **1978:** Raytheon patented ferroelectric IR detectors using Barium Strontium Titanate (BST).
- **Late 1980s:** Microbolometer technology developed.
- **1980s–1990s:** Significant focus on 2D InSb and uncooled device technologies. MCT technology efforts focused on Gen 2 scanning devices.
- **1990s–2000s:** Initial technology development on MCT dual-band devices; MCT, InSb, and uncooled 2-D staring devices used widely in applications such as targeting and surveillance systems, missile seekers, driver aids, and weapon sights.

Significant efforts have been undertaken to insert these now-proven IR devices into military payloads and missile seekers, and later into commercial products. As

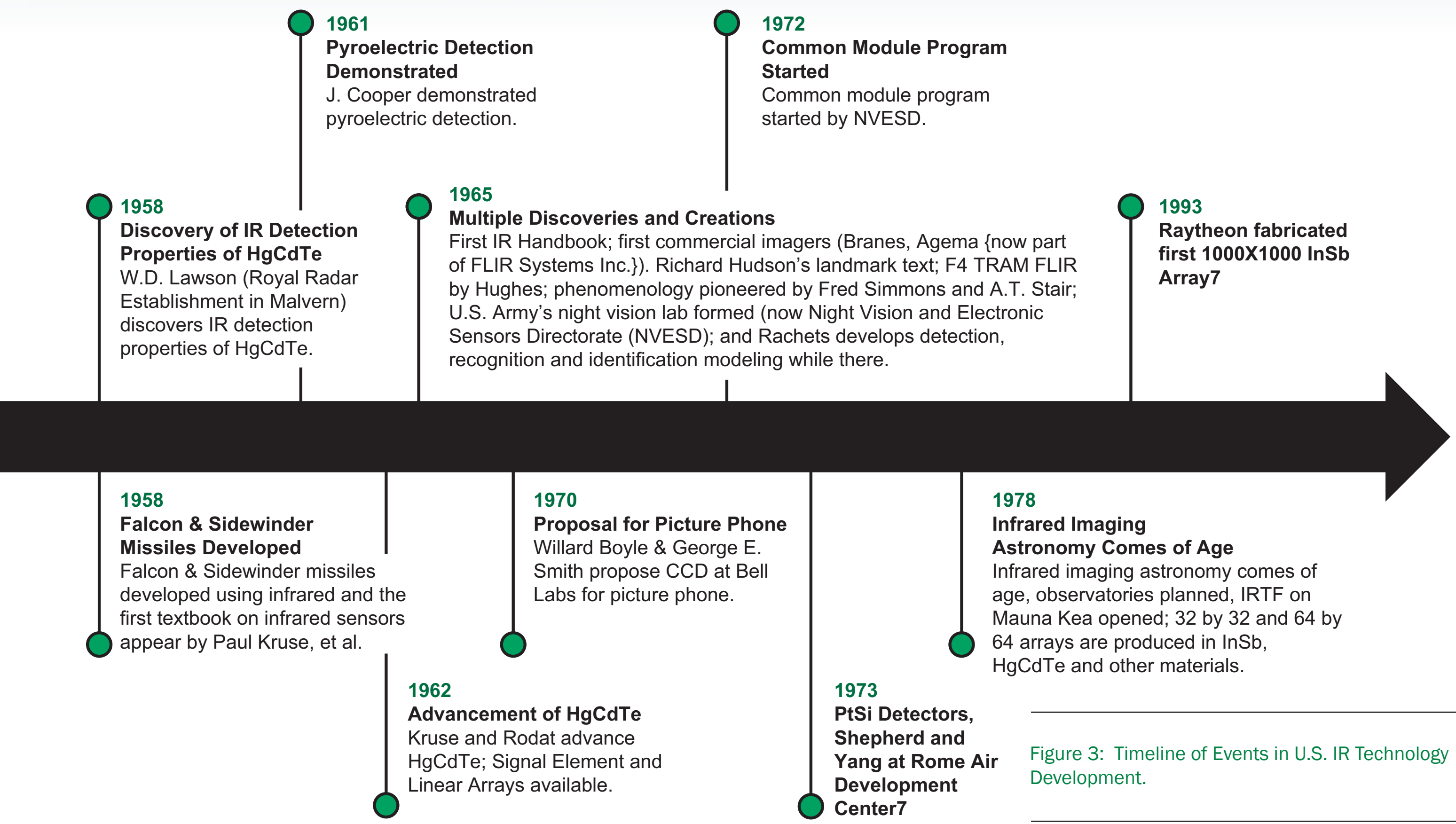

Figure 3: Timeline of Events in U.S. IR Technology Development.

a result of the success of military research and development programs, new applications were identified and products were moved into production. Thermal imaging technology provided the ability to see and target opposing forces through the dark of night or across a smoke-covered battleground. Not surprisingly, these properties validated the Army's claim of owning the night, at least for the better part of two decades (from 1970 to about 1990).

CURRENT TRENDS, NEEDS, AND FUTURE PROJECTIONS

The reality today is that the U.S. military "shares the night" with its adversaries. But our future defense posture depends upon making sure we corner the greatest share of that night. Currently, threats often come from adversaries that employ unconventional tactics, but that fact doesn't mean we can ignore adversaries that employ conventional tactics as well. Furthermore, we have traditionally chosen to avoid close combat in cities, preferring instead to use our superiority in long-range-standoff weapons to defeat conventional forces. However, evolving world demographics coupled with political turmoil have increasingly drawn conflict and warfare into urban areas, especially in parts of the world that have become increasingly unstable for various reasons. These urban populations provide a large, ideal environment for enemy combatants to hide and operate in as well as a challenge for U.S. forces to try to deploy conventional weapons and tactics. Hence, there is a great need for an extensive strategizing, reequipping, and retraining of the U.S. military to successfully cope with urban warfare. New high-performance IR imaging systems already play a critical role in this type of warfare, and an even bigger role will likely be played by more advanced systems currently in development.

Ultimately, success in urban warfare largely depends upon one's ability to accomplish the following (as adapted from Carson [7]):

> The "Holy Grail" of imaging systems has long been to provide their own ability not only to see but to understand what they are seeing.

- Find and track enemy dismounted forces, even when their appearance is brief or mixed with the civilian population.
- Locate the enemy's centers of strength (e.g., leadership, weapons caches, fortified positions, communication nodes, etc.), even when camouflaged or hidden in buildings.
- Attack both light and heavy targets with precision, with only seconds of latency and little risk to civilian populations and infrastructure.
- Protect U.S. forces from individual and crew-served weapons, mines, and booby traps.
- Employ robots in the form of drones, such as unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) as well as unattended sensors.
- Protect our own forces and homeland infrastructure from these same drones, which, in miniature, can fly in undetected while carrying miniature IR sensors that allow for precise day/night delivery of explosives.

To meet these requirements, imaging systems must provide persistent surveillance from platforms located almost directly overhead and from small, stationary, and maneuverable platforms on the ground. Also needed are imaging systems that perform targeting and fire control through haze, smoke, and dust. Overhead systems must have the resolution to recognize differences between civilian and military dismounts. Some of them must have the ability to perform change detection based on shape and spectral features. Others must have the ability to quickly detect and locate enemy weapons by their gun flash and missile launch signatures.

Near-ground systems must have the resolution and sensitivity to identify individuals at relatively short ranges from their facial and clothing features and from what they are carrying. These systems must also be able to accomplish this identification through windows and under all weather and lighting conditions. Some systems must also be able to see through obscurations, such as foliage and camouflage netting. In addition, in most cases, collected imagery will be transmitted to humans who are under pressure to examine it and make quick, accurate decisions. As such, it is important that imagery be of a quality that is highly intuitive and easily interpretable. This persistent "up close and personal" sensing strategy requires many and varied platform types. Cost is also an important factor in this equation, due to ongoing budget constraints. Both the sensors and the platforms that carry them must be smaller, lighter, and more affordable.

Solutions to some of the surveillance requirements are being addressed with advanced persistent surveillance systems, such as ARGUS-IS and ARGUS-IR (illustrated in Figure 4). ARGUS-IS has an enormous array of 368 optically butted FPAs using 4 co-boresighted cameras. They combine for a total of 1.8 gigapixels that can provide separate images of 640×480 pixels to as many as 65 operators. The operators can independently track separate ground objects or persons of interest within the ground footprint of the combined sensors with a ground resolution of approximately 4 inches at a 15-kft platform altitude. ARGUS-IS operates in the visible/near IR (V/NIR) spectral band and requires daylight, but the Department of Defense (DoD) is developing the more advanced MWIR version (ARGUS-IR) to field comparable capability at night. ARGUS-IR will provide more than 100 cooled FPAs each with 18 megapixels [8–11].

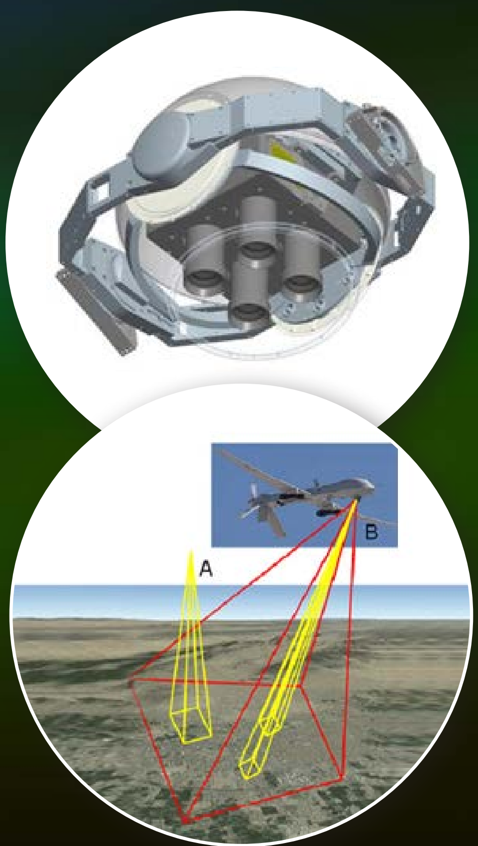

Figure 4: The ARGUS-IS Persistent Surveillance System [8–11].

On the opposite side of the IR sensor form factor spectrum are miniature IR surveillance technologies, such as the uncooled LWIR microbolometer pictured in Figure 5. These types of sensors are being used in both commercial and military applications. Because of their small size, they have an inherently low size-weight-power-cost (SWaPC) and can be deployed by a variety of means in a variety of terrains and urban environments. They can run unattended for a long time on batteries, are capable of taking pictures that can be recorded or transmitted, and, in general, are so inexpensive that they can be considered expendable.

While the emergence of small surveillance drones has driven the need for lower weight and lower volume payloads, in some cases, performance cannot be sacrificed, and microbolometers cannot meet all of these needs. In these instances, there is on an ongoing drive for small-pitch FPAs that operate at higher temperatures, often above 150 K. Overall sensor size, for equal performance, scales with detector pitch as long as the aperture size is maintained. Smaller pixels allow for a reduction in the dewar and cooler size as well as reductions in weight and size of the optics. Accordingly, package size and, to a large degree, package weight can be reduced in proportion to detector pitch. The current trend appears to be moving to 10–8-μm pitch for MWIR sensors, but some LWIR FPAs are being made with a pitch as small as 5 μm.

Readily available commercial microbolometers are a potential security threat to U.S. forces even though these imagers have lower resolution and sensitivity than what advanced technology can provide. Ironically, their presence requires our forces to have even more advanced technology because our enemies are uninhibited by protocols and will typically fire on

Figure 5: The FLIR Inc. Lepton Microbolometer.

our forces using only inexpensive sensors that provide low-resolution images, which are inadequate for target identification. U.S. forces, on the other hand, are authorized to fire only when the enemy can be positively identified. Thus, the enemy's sensors effectively give the enemy a major range advantage. It is hoped, however, that the emerging systems currently under development will trump this advantage and provide an answer for the proliferation of IR imagers in the hands of our adversaries.

The Army's desire for increased standoff range resulted in the emergence of a third generation (Gen 3) of staring sensors with both MWIR and LWIR capability. The shorter MWIR wavelength offers nearly twice the range of the LWIR band in good weather, but the LWIR band excels in battlefield smoke and dust and provides greater range in cold climates. One of the particular challenges for the Gen 3 systems is reducing cost. The high cost is generally associated with both low detector yield and complex optics. Reducing the detector cost is being explored on two fronts: alternate substrates and new detector materials. A Gen 3 detector is made by placing an MWIR detector material behind LWIR material so the two bands occupy the same space in the focal plane. Only two materials currently offer the potential to accomplish this effect: MCT and superlattices. MCT is most easily made on CdZnTe substrates because both material's crystal lattices match well, thus providing higher yield. However, lower cost GaAs and Si substrates are also being explored with considerable success.

The other front exploits the potential for a radically different material type called a superlattice. Superlattices exploit nanotechnology to engineer materials from the III–V columns of the periodic table to make alloys from InAs and GaSb. In principle, superlattices have many favorable characteristics, such as being strong, stable, and inexpensive. However, they have wide band gaps. So, to detect low-energy MWIR and LWIR photons, they have to be fabricated in thin alternating layers to form quantum wells. These structures have the additional benefit of being compatible with another breakthrough in detector design, that of negative-barrier-negative (nbn) junctions. These junctions have an advantage over traditional positive-negative (pn) junctions (such as are commonly used in commercial solar cells) in that they can better suppress the dark current that arises from latent heat in the material. This, in turn, offers the potential for higher temperature operation. Current success so far has largely been in the MWIR region, but the expectation is that success will eventually be attained in the LWIR region as well. It remains to be seen if it will offer a better solution than MCT detectors.

> It is projected that an entire Intel 8086 microprocessor will fit within a single 30-µm-square pixel by the year 2018.

The dual-band Gen 3 approach is actually a subset of multispectral and hyperspectral imaging. These imaging types offer additional modalities and are often best exploited through the use of sensor fusion techniques. But they face several technological challenges and are still in development. Multi-spectral images must be displayed or processed simultaneously in each band to extract target information. Additionally, for operator viewing, they must be combined into a single composite image using a color vision fusion approach. The best approach for accomplishing the image fusion and operator display is currently being investigated. However, initial results have shown impressive reductions in false alarm rate and probability of missed detections when, for instance, searching for targets hidden in deep tree canopies and/or under camouflaged nets.

Airborne and naval platforms have taken an entirely different approach to gaining extended range target identification. Their approach can, in principle, triple the range of existing targeting FLIRs. These platforms are adopting passive/active hybrid systems consisting of passive IR imaging for target detection in combination with active LADAR (a combination of the words "laser" and "radar") for high-resolution identification. Pictured in Figure 6 are example

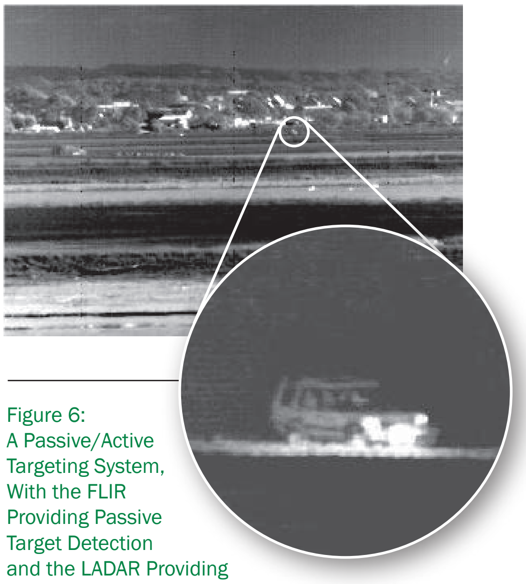

Figure 6: A Passive/Active Targeting System, With the FLIR Providing Passive Target Detection and the LADAR Providing Active Identification [12] (Copyright BAE, UK, All Rights Reserved).

Figure 7: The USAF LITENING G4 LTIP Pod Using Active Imaging for Extended Range Target ID (Northrop Grumman).

images provided by BAE. In principle, LADARs can image with much shorter wavelengths, 1.54–1.57 μm, to greatly reduce the diffraction blur diameter of the optics with a corresponding increase in range. Moreover, this choice of wavelengths is eyesafe. These systems have just recently been fielded on aircraft and ships. Figure 7 shows a picture of the Air Force's Laser Target Imaging Program (LTIP) pod.

Perhaps the biggest breakthrough in this area, however, is about to be achieved. The "Holy Grail" of imaging systems has long been to provide their own ability not only to see but to understand what they are seeing. For instance, drones are merely flying platforms that are useless without their data link. And in future combat, data link survival is not assured. Soon, LADARs are expected to solve the challenge of image understanding in autonomous systems by advancing to 3-D shape profiling of targets. Current 2-D "automatic target recognition" technology has yet to accomplish that advancement in spite of millions of dollars and more three decades of research [10]. But if targets can be profiled in 3-D and then compared to a stored library of 3-D wireframe target models, the goal might finally be achieved. That is because it would be highly unlikely to mistake an object for a false target when it is accurately compared in three dimensions and when it is presented with an appropriate FLIR thermal signature as well. And one can only wonder if hybrid 3-D LADARs/FLIRs might one day even open up the battlefield to the real Holy Grail—the replacement of a human warrior on the battlefield with a robot warrior.

Passive/active fused sensors also promise to provide a solution to one of the more ominous threats facing our nation from domestic terrorism—the wide availability of cheap micro-drones equipped with thermal cameras and capable of carrying explosives. Threats such as these, which could be flown out of the trunk of a car at night, could ostensibly be made with radar cross sections too small for expensive and bulky conventional air defense radars to detect, thus potentially holding hostage the entire infrastructure of a nation. Moreover, radars might have to be placed on almost every corner to avoid structural masks.

On the other hand, small, compact, and inexpensive laser scanners, such as those used on some self-driving automobiles today, could be widely deployed around critical infrastructure, such as military installations, financial centers, and the power grid. They could establish a 3-D reference space of known objects and then cue off of change detection whenever new objects enter that space. Their high resolution could permit object identification; and ultimately, when equipped with higher power adjunct lasers, they could be able to dazzle or otherwise blind the drone's sensors, if not destroy the drone outright. Such a defense would be far preferable to using gun fire or missile interceptors in densely populated urban areas. Thus, passive/active IR sensors are not only transformative on the battlefield they offer the promise of being transformative everywhere.

Finally, there is at least one more transformative emerging IR technology, and it is already being tested. This involves digital readout integrated circuits (DROICs) now in development [14]. Recall that all Gen 2 and Gen 3 FLIRs, as well as many LADARs, are enabled by analog ROICs. These devices provide the critical capability required to multiplex millions of parallel detector signals into a serial output signal placed onto a single wire. A major problem they have, however, is the lack of charge storage capacity. IR scenes produce enormous "background" flux, and the desired signal is only a small percentage of that flux. Existing ROICs cannot store the resulting charge in their pixels and must instead shorten their integration time to discard the additional charge. Of course, the signal also gets discarded at the expense of sensitivity.

However, DROICs are redefining the paradigm because they "count" the photoelectrons as they are being generated before they are discarded. This breakthrough capability is the result of Moore's law in microelectronics. It is projected that an entire Intel 8086 microprocessor will fit within a single 30-μm-square pixel by the year 2018, when 7-μm feature sizes are expected to become available! And it isn't just sensitivity that stands to improve, but signal processing as well. With so much processing power embedded in each IR pixel, it will be possible to implement such space- and power-hungry off-chip tasks as image stabilization, change detection, passive ranging from optical flow calculations, super-resolution, and time-delay-and-integration. LADARs will be able to perform range measurements within each pixel to high accuracy, which will enable them to measure the shape of even small objects and thus improve their ability to identify hand-held threats, such as handguns. Inarguably, such capabilities are on the verge of yielding still more transformative changes in IR technology.

CONCLUSIONS

IR technology remains a key component in the U.S. defense posture, and it is hard to imagine how the country would

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defend itself without the benefit of IR surveillance and targeting systems. However, as with most technologies, IR technology is also diffusing throughout the world, making our current advantage but an instant in time. And if we consider the implications of the historian's famed adage—"those who ignore the lessons of history are condemned to repeat them"—we recognize how truly ephemeral this advantage is. Thus, it is not the current advantage that is key; rather, it is the rate of technical advancement that is important.

To be sure, the U.S. IR advantage can be sustained if we retain some of the policies and pathways that got us to where we are today. These policies include continuing to find and secure adequate DoD funding. Admittedly, these funds are chronically limited, so we must also continue to leverage and optimize them as much as possible. In the past, this leverage and optimization have been achieved via close working relationships between government laboratories, industry, and academia. Particularly important have been the role of IRIS and the MSS in sponsoring regular meetings. Those meetings promote technical exchanges at a level that helps all while not undermining the benefits of healthy competition.

Technology leverage and optimization have also been successfully achieved through large, collaborative programs, such as the DoD-funded Vital Infrared Sensor Technology Acceleration (VISTA) program, which seeks to develop a baseline of shared technical knowledge and fabrication infrastructure. Through such programs, each participating company does not have to make a separate, redundant investment in critical underpinning capabilities, yet it can add value by the way it manages the products and innovates beyond that framework.

Finally, advances in IR technology have been, and will continue to be, largely driven by advances in materials and in microelectronics. The latter area is advancing exponentially by Moore's Law. Thus, one can expect the already breathless pace of advancements to be even more rapid going forward. ■

BIOGRAPHIES

JAMES "RALPH" TEAGUE is a principal research scientist at the Georgia Tech Research Institute (GTRI) with more than 44 years of experience in sensor and related technologies, encompassing material science to large-scale sensor system integration. Dr. Teague currently serves as a technology specialist supporting DSIAC, responding to technology inquiries from the military and homeland defense sensing communities. He provides short courses to the sensor community in detection and tracking systems; laser systems; missile seeker design; EO/IR payloads; self-defense systems; chemical, biological and explosion detection systems; as well as required sensor-related technologies, such as detectors, image processing, and optics. Dr. Teague is also active as a technology advisor, consultant, and expert witness and has also been an Associate Editor for the IEEE Aerospace and Electronic Systems magazine, responsible for sensors, EO, and radar content. He holds a Ph.D. in experimental physics from the University of Missouri-Rolla, an M.S. from New Mexico Highlands University, and a B.A. from the University of North Carolina.

DAVID SCHMIEDER is a retired principal research scientist at GTRI and a consultant specializing in IR systems analysis with experience ranging from target acquisition and missile seeker design to defensive suite selection for platform protection. Before joining GTRI, he worked as an IR/EO systems designer and analyst on armor, helicopter, and fixed-wing fire control systems at Lockheed Martin and Delco/Hughes/Raytheon. While at Lockheed Martin he was the lead IR/EO systems engineer on the Apache TADS/PNVS targeting and navigation system. At GTRI, he was among the first to investigate and publish the effects of clutter on targeting system performance and on stealth platform detectability. In addition, Mr. Schmieder started the IR/EO professional education program at Georgia Tech, which was the first in the nation to offer formal training in limited access content describing U.S. military IR/EO targeting, countermeasures, and stealth technology. He holds a M.S. in physics from Kansas State University and is a Fellow of the Military Sensing Symposia (MSS).

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DTIC SEARCH TERMS:

Infrared Technology

RESULTS: 245,000

- Infrared Detection & Detectors (3,300+)
- Optics (2,575+)
- Sensors, Electronics, & Electronic Warfare (2,200+)
- Lasers & Masers (1,707+)
- Infrared Detectors (1,688+)
- Air & Space Superiority (1,500+)
- Electro-Optical Sensors Technologies (1,500+)
- Electrooptical & Optoelectronic Devices (1,500+)
- Electro-Optic & Infrared (EO/IR) Sensors (1,400+)
- Other (8,100+)

*See page 16 for explanation ▸

SAFETY HAZARDS

IN THE ENERGETICS LABORATORY

By Andrew Taylor

INTRODUCTION

During the research and development (R&D) of new and novel energetic materials, researchers face a myriad of technical and safety challenges in the laboratory that need to be addressed and overcome. The extremely volatile nature of energetics requires particular attention and vigilance. While the exact number of accidents resulting in injury or death is not easily obtained, the Chemical Safety Board—an independent federal agency charged with investigating industrial chemical accidents—has gathered preliminary information on 120 university laboratory accidents since 2001 that have resulted in 87 evacuations, 96 injuries, and 3 deaths [1].

This article discusses the challenges of working with energetic materials in the laboratory and provides guidance on process development and safety equipment that can be used to reduce the associated risks.

Whether it be from the toxic precursors or the sensitivity of the synthesized energetic, energetic materials safety requires a multi-pronged approach that begins with defining the task to be performed and developing a project plan. The inherent danger of working with energetic materials in the laboratory requires the researcher to develop a comprehensive safety plan and scale-up procedure. While accidents are not common, when they do occur, they result in significant injury, often to the hands and arms, which are typically most at risk due to the close proximity to the energetic material.

Hazardous chemicals can present both physical and health threats. Chemicals encountered during the development phase may include carcinogens; toxins that may affect the liver, kidney, or nervous system; irritants; corrosives; and sensitizers; as well as agents that act on the blood system or damage the lungs, skin, eyes, or mucous membranes. In addition to the health threats posed by the hazardous chemicals present in the laboratory, working with materials having the potential to form explosive mixtures or compounds requires special precautions, as some explosives are sensitive to small amounts of stimuli in the form of friction; impact or shock; electrostatic discharge (ESD); or heat.

PROCESS DEVELOPMENT

Key to any project involving explosives is a well-thought-out process that requires critical thinking before, during, and after the project for continuous safety in any laboratory. First, it is important to identify hazards and implement controls to address those hazards before beginning a project. Then, during project execution, the effectiveness of the controls should be constantly evaluated, and any adjustments should be made and captured as modifications to the operating procedures governing the operation. And once the work is complete (as well as during the project), all unusual incidents, mishaps, or unexpected chemical reactions should be captured and kept within a laboratory central repository for others to access. This repository can serve as a "lessons learned" library and should be consulted prior to the start of any new activities. Adjustments to procedures should be made as needed to accommodate for any possible hazards associated with the material.

Figure 1 illustrates the steps for developing a comprehensive safety program when working with energetic materials. Safety program development starts by defining the task, including each interim step and the identified hazards, and concludes with the execution of work and the associated lessons learned [2].

HIERARCHY OF HAZARD CONTROLS

Safety is the responsibility of personnel within all levels of an organization

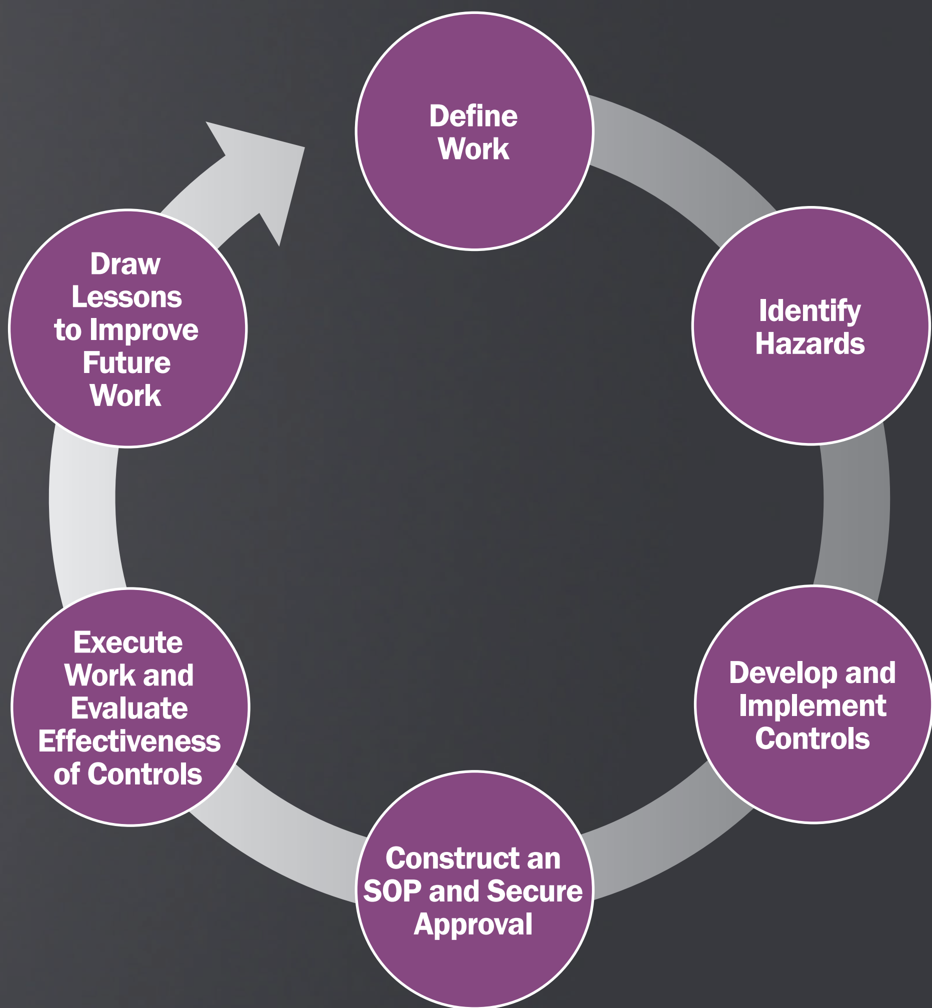

Figure 1: Steps in Developing a Comprehensive Safety Program.

involved in energetic materials R&D. From the laboratory personnel to the facility manager, these personnel are responsible for conducting thorough procedural safety reviews (internal to their organization and/or through technical community peers) before commencing synthesis or formulation operations.

Each level of an organization carries responsibilities and implements corresponding controls to assist with those responsibilities. The concept of the Hierarchy of Controls described in the Laboratory Standard, 29 C.F.R. § 1910.1450, prioritizes intervention strategies based on the premise that the best way to control a hazard is to systematically remove it from the workplace, rather than relying on employees to reduce individual exposure [1]. As indicated in Table 1, the four types of measures that may be used to protect employees (listed in decreasing order of effectiveness) are (1) elimination or substitution, (2) engineering controls, (3) administrative controls, and (4)personal protective equipment (PPE).

> Key to any project involving explosives is a well-thought-out process that requires critical thinking before, during, and after the project.

Elimination or substitution of hazards can be accomplished by modification of existing equipment and material acquisition programs. Engineering controls, such as chemical hoods, physically separate the employee from the hazard. Administrative controls, such as employee scheduling, and development of standard operating procedures (SOPs), are established by management to help minimize the employees' exposure time to hazardous chemicals. Finally, protective clothing and PPE are additional protection provided under special circumstances and when exposure is unavoidable.

PROTECTING PERSONNEL

The key hazards posed by an initiating explosive are noise, fragments, blast, and heat. There are also secondary effects, such as the ignition of nearby flammable materials, the formation and release of harmful gases, and chemical contamination.

Note that elimination or substitution (use of an analog), while most effective at reducing hazards, also tends to be the most difficult measure to implement. Furthermore, the use of engineering controls is usually the most effective way to protect all laboratory workers because these measures make changes at the source of the hazards and do not rely on the skill or vigilance of individuals. The basic concept behind engineering controls is that, to the extent feasible, the work environment and the task itself should be designed to eliminate hazards or reduce exposure to hazards.

Title 29 of the Code of Federal Regulations, specifically C.F.R. § 1910.132, requires employers to ensure that PPE be provided, used, and maintained in a sanitary and reliable condition to prevent injury. Unfortunately, choosing the proper PPE can often be challenging as most equipment is not tested against the effects of an unintended initiation that can result in fragmentation hazards and blast overpressures.

Table 1: Hierarchy of Hazard Controls

HIERARCHY OF HAZARD CONTROLS

	Control	Examples
MOST EFFECTIVE	1. Elimination or Substitution	• Replacing of toxic substances with nontoxic alternatives • Updating/replacing process equipment
	2. Engineering Controls (Safeguarding Technology)	• Using safety shields • Using fume hoods
	3. Administrative Controls (Training and Procedures)	• Establishing/maintaining well-defined work practices • Reducing the time workers are exposed to a hazard • Providing necessary training
LEAST EFFECTIVE	4. Personal Protective Equipment (PPE)	• Using coveralls • Using gloves • Using eye protection • Using hearing protection

PROTECTIVE SHIELDS

Engineering controls such as a blast shields can minimize the risk to personnel by protecting personnel from the resulting blast effects from an unintended initiation. Military Standard (MIL-STD) 398A [3] specifies that shields shall be designed to prevent exposure of operating personnel to peak positive incident pressures greater than 2.3 psi (15.9 kPa), which is below the threshold for a disabling injury, and heat flux should be limited to prevent the onset of second-degree burns.

Users of PPE must be aware that the equipment does not eliminate the hazard.

The U.S. Naval Surface Warfare Center at Indian Head, MD, conducted testing looking at the blast overpressures and heat flux imparted on both standing and sitting operators resulting from the detonation of ~2.6 g and ~11.5 g of PBXN-5 pellets using Reynolds RP-80 detonators containing 0.2 g of explosive. Test results showed that properly designed shields provide adequate protection against blast over pressures and heat flux [4]. The U.S. Department of Energy (DOE) Explosives Safety Manual (DOE M 441.1-1A) lists shields that have been tested and found acceptable for the indicated quantities of explosives [5].

In addition to the testing conducted by the DOE, the Atomic Weapons Establishment (AWE) tested a number of commercially available safety shields to assess the level of protection provided [3]. The shields were tested against detonating charge masses of 0.3 g, 1 g, 5 g, and 7.5 g for PETN-based explosives, and 1.3 g for an HMX-based explosive. The fragment sources used in the trials were Glass Round Bottom Flask (RBF), Porcelain Buchner Funnel (BF), or Glass Test Tube (TT). Complete details on charge selection, composition, and test configurations can be found in DOE M 441.1-1A [5].

PPE

Physical hazards encountered while working with energetic materials pose a significant challenge in the implementation of PPE. The selected PPE must provide adequate protection while also not excessively inhibiting dexterity and grip, which could introduce additional hazards. Using PPE requires hazard awareness and training on the part of the user. Users must be aware that the equipment does not eliminate the hazard. If the equipment fails, exposure may occur. Thus, when selecting the proper PPE, employers and employees must understand the equipment's purpose and its limitations.

As mentioned, the hands and arms are typically most at risk when working with energetic materials in the laboratory due to the close proximity to the material being manipulated. Hand and arm injuries can result in a permanent loss of motoric function. To help mitigate these injuries, protective equipment includes gloves, finger guards, and arm coverings or elbow-length gloves. Tests conducted at AWE have shown as little as 0.3 g of PETN-Sylgard 182 explosive paste is capable of causing significant injury at small standoff distances when surrounded by a suitable fragment source [6].

Hand and arm protective wear is evaluated on its ability to provide protection from mechanical damage, including punctures, cuts, abrasions, fractures, and amputations, as well as protection against heat and chemical contamination. Unfortunately, the current standards for testing against mechanical damage, EN 388 and ANSI/ISEE 105, are not representative of the hazards posed by a small-scale explosive event and therefore do not accurately represent the threat. Klapötke et al. [8] and Murray et al. [7] tested a variety of gloves and wrist and arm protectors to assess the level of protection offered by various materials, as well as limits on motoric function. Complete details on glove selection and test results are provided in these references [7,8].

CONCLUSION

The development of energetic materials can be a risky endeavor. Whether they be in an academic setting, National laboratory, or a Defense facility, researchers and laboratory personnel need to ensure proper measures are in place to manage the risks. Having a detailed plan listing each step and the

associated hazards is important to ensure the safety of personnel. While the literature offers some guidance on the selection of safety equipment, it also shows a gap in test standards and the addressing/mitigation of hazards encountered in the energetics laboratory. Accordingly, efforts are needed to close this gap and further protect personnel working in this area. While federal, state, and local regulations should be consulted and followed, it is also important to conduct an independent assessment of the project being performed, the hazards associated with the chemicals involved, and the environment that the project is being conducted. This assessment will aid in the identification of potential hazards and allow for safety measures to be put in place to mitigate these hazards. And as always, caution and knowledge will continue to be the keys to safe work practices when handling energetics. ■

NOTE

The research in this area was accomplished in tandem with a federally sponsored Chemical Propulsion Information Analysis Center (CPIAC) project on the collection of standards and best practices for safely handling improvised and homemade explosives.

BIOGRAPHY

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DTIC SEARCH TERMS:

Energetic Material Safety

RESULTS: 30,500

- Foreign Reports (3,400+)
- Ammunition & Explosives (3,100+)
- FBIS Collection (2,500+)
- Government & Political Science (2,400+)
- Symposia (2,009+)
- USSR (1,600+)
- Explosives (1,424+)
- Test & Evaluation (1,300+)
- Safety (1,120+)
- Economics (1,100+)

*See page 16 for explanation ▸

UPCOMING WEBINARS

UAS Airspace Integration: Updates, Progress and a Path Forward

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http://www.auvsi.org/events/eventdescription/?CalendarEventKey=bfbe0eaa-621b-47ce-a30f-e875c794cbb3 ▸

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http://www.auvsi.org/events/eventdescription/?CalendarEventKey=1336c18f-9906-44df-b7b0-32c29d9c603e ▸

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OCTOBER 2015

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5–8 October 2015
Rosen Plaza
Orlando, FL
http://www.savecenter.org/symposium.html

Cyber Electromagnetic Activity 2015
6–8 October 2015
Water's Edge Events Center
Aberdeen, MD
http://crows.org/event/192-aoc-conferences/2015/10/06/34-cyber-electromagnetic-activity-2015.html

2015 AUSA Annual Meeting and Exposition
12–14 October 2015
Walter E. Washington Convention Center
Washington, DC
http://ausameetings.org/2015annualmeeting

UAS Propulsion: Optimization, Technical Challenges and Future Directions
14 October 2015
The American Institute of Architects
Washington, DC
http://www.auvsi.org/events/eventdescription/?CalendarEventKey=d3f8bd7d-8f06-4182-9bce-00cb3303ad84

MILCOM 2015
26–28 October 2015
Tampa Convention Center
Tampa, FL
http://events.jspargo.com/milcom15/public/enter.aspx

18th Annual Systems Engineering Conference
26–29 October 2015
Waterford at Springfield
Springfield, VA
http://www.ndia.org/meetings/6870/Pages/default.aspx

AHS International Specialists' Meeting on Propulsion
27–29 October 2015
Fort Magruder Hotel and Conference Center
Williamsburg, VA
http://www.vtol.org/events/ahs-international-technical-meeting-on-propulsion

20th Annual Expeditionary Warfare Conference
27–29 October 2015
Renaissance Portsmouth - Norfolk Waterfront Hotel
Portsmouth, VA
http://www.ndia.org/meetings/6700/Pages/default.aspx

2015 Precision Strike Technology Symposium (PSTS-15)
27–29 October 2015
Johns Hopkins University Applied Physics Laboratory
Laurel, MD
http://www.precisionstrike.org/Events/6PST/6PST.html

Marine Corps Spectrum Maneuver Warfare
27–28 October 2015
MCCS Cherry Point Two Rivers Theater & Event Center
Havelock, NC
http://crows.org/event/192-aoc-conferences/2015/10/27/24-marine-corps-spectrum-maneuver-warfare.html

Unmanned Systems Defense
27–29 October 2015
The Ritz-Carlton, Pentagon City
Arlington, VA
http://www.thedefenseshow.org/usd2015/home

NOVEMBER 2015

53rd Annual SAFE Symposium
2–4 November 2015
aribe Royale All-Suite Hotel & Convention Center
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http://www.safeassociation.com/index.cfm/page/symposium-overview

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3–4 November 2015
Emerald Coast Convention Center
Ft. Walton Beach, FL
https://www.regonline.com/builder/site/Default.aspx?EventID=1714488

Aircraft Survivability Symposium 2015
3–5 November 2015
Naval Postgraduate School
Monterey, CA
http://www.ndia.org/meetings/6940/Pages/default.aspx

AAAA Survivability & Support Week
16–19 November 2015
Von Braun Center
Huntsville, AL
http://www.quad-a.org/events/index.php/alse-ase-cribbins-home

Future Ground Combat Vehicles 2015
16–18 November 2015
Detroit, MI
http://www.groundcombatvehicles.com

DECEMBER 2015

Global Demilitarization Symposium
7–9 December 2015
Hilton Parsippany
Parsippany, NJ
http://www.ndia.org/meetings/6580/Pages/default.aspx

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