# Data Visualization and Large-Scale Battlespace Simulations: Challenges, Opportunities and Emerging Technologies

*E. Philip Amburn*
*Dept. of Computer Science*
*University of Arizona*

amburn@cs.arizona.edu

*Dan M. Davis*
*HPC-Education*

dmdavis@acm.org

*Robert F. Lucas & Gene Wagenbreth*
*Information Sciences Inst.*
*Univ. of Southern California*

{rflucas, genew}@isi.edu

**Abstract:** *This paper examines the special data visualization needs and challenges presented by large-scale battlespace simulations. Within the last decade, intelligent agent simulations have been enabled by high-performance computing to reach levels exceeding ten million entities (individual personnel, vehicles, weapons systems, etc.). These large-scale simulations create incredibly large sets of data in very short periods of time. Managing this data is a field of research of its own, but optimally exploiting this flood of data is even more challenging. The authors assert that, while the high-performance computers have created this problem, newly developed capabilities utilizing these same capabilities can and should be implemented to assure the warfighters are given the information they need most, when they need it, and in a form that will have the best chance of producing the correct outcome. This is based on their experience in visualization, high-performance computing, large-scale simulations, and military operations both in academic research and active duty military service or intelligence analysis. The paper recounts and alludes to historical examples of the difficulties in effectively conveying information within the chain of command, supporting the notion that these problems are neither unique to simulation nor are they issues that can be ignored, especially when solutions are at hand. Special emphasis will be put on new ways to convey the range of alternatives and communicate the relative likelihood of the predictions of future conditions, dispositions and actions, all without swamping the users with too much data. A survey of associated topics like causal modeling and behavioral science insights will also be presented along with analysis as to their contribution to better exploitability of the computer-generated insights. The paper concludes with recommended approaches for studying, evaluating and implementing the most promising techniques and technologies.*

## About The Authors

### I. Introduction

This paper is an analysis of the current state of information-transfer procedures used to convey the insights gleaned from data collection, analysis and simulation of battlespaces. Both real and simulated battlespaces include all the personnel engaged: both combatants and non-combatants. The focus here is on the requirements and challenges flowing from the creation of immense data sets generated by large-scale computer-enable simulations, but the lessons learned and the technologies discussed are obviously applicable to analog situations in other contexts, *e.g.* active battlespaces and live combat situation awareness. The authors identify, characterize and analyze the problems of effectively visualizing battlespace data and discuss those problems' amenability to emerging techniques and technologies.

Battlespace simulations are traditionally recognized as tools that can be used to provide training, analysis, and evaluation, but they have also recently been proposed as having a potential for "look-ahead" capabilities to support situation awareness. With mission success and personnel lives at stake, the pressures on the military leadership are intense, so this predictive use is vital, but fraught with potential break-downs in the computer/human interface. As the abilities of simulation systems to reliably predict future conditions improve, this use is expected to increase in prevalence and grow in importance, thereby becoming pervasive.

The paper continues with a section setting forth a description of the central issue at hand and presenting some historical context for some of the more vexing problems. It will then review the impact that computer simulations have had, focusing especially on the authors' experience with large-scale military simulations that were enabled by distributed high performance computing. These implementations began in earnest with the SF Express project early in the 1990's (Messina, 1997a). That and follow-on initiatives have generated so much information that two meta-challenges have arisen: data management and data visualization, *i.e.* effectively recognizing and conveying the insights from that data to the DoD consumers.

The next major section will treat the nature and extent of the challenges that have been observed in the data communications area. Both problems from operational experience and the issues experienced during large-scale simulations will be described and analyzed.

In addition to these observed and named needs, the paper will raise and discuss several new opportunities to aid the warfighters to better utilize the data that is available. The manner in which data is presented is a major thrust of this paper. This field is usually referred to as data visualization. There is extant a term: "visulation," which was coined to represent the combining of the simulation and data visualization functions. To accent the utility of visualization for both simulation and live combat, this term will not be emphasized.

Several new technologies and techniques will be discussed in the "Emerging Technologies" section, applying experience from previous large scale simulations and on-going intelligence operations to assess the potential of these emerging capabilities.

The paper will conclude with a discussion of the future that lays ahead, the most promising research approaches and the need for closer liaison with the warfighters.

## II. Background

As long as there has been warfare, there have been efforts to better prepare for the literal life and death struggles that will inevitably occur. As long as combat preparation has been practiced, surely there have been the questions as to whether or not these efforts have been germane, practicable, and efficacious. Clearly a major issue is whether the lessons and skills sought to be imparted are effectively inculcated in the learner. Computation science has delivered an entirely new set of tools for the preparation, capability-transfer, and training evaluation segments of these evolutions.

The authors were all engaged in teams that implemented high-performance computing (Davis, 2010) and communications (Davis, 2005) to enable expanded and enhanced modeling and simulations capabilities.

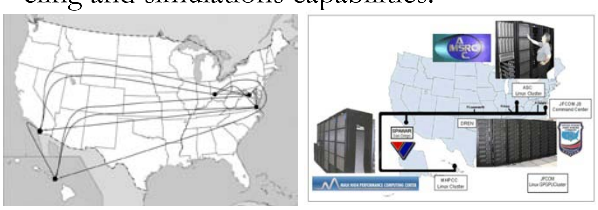


**Figure 1 - Advanced Broad Bandwidth Communications Network for Joint Urban Ops and Linux Cluster Meta-Computing for JFCOM Urban Resolve Experiments (Davis 2005 & 2010)**

In a live operational setting, there are analogous issues: How does a person effectively communicate intelligence, give direction or conduct analysis within the chain of command? A historical example of this perplexing issue is taken from the middle of World War II. In early June of 1944, Gen. Eisenhower was faced with an almost paralyzingly critical decision: When to launce the invasion of France. Two major parameters were weather and sea-state (Logan, 2013). Ike had to rely on his chief weather forecaster, Group Captain James M. Stagg, to brief him on this issue. Group Captain Stagg had been in meteorology for two decades and he faced a critical, but not uncommon, conundrum: How to distill twenty years of technical experience down to usable nugget so that a commander under stress could make a rational, or preferably optimal, choice. Thousands, if not tens of thousands of lives depended on making the best decision (D-Day Museum, 2014). The meteorological analysis itself was essentially stochastic; the forecast based on a certain amount of intuition. Group Captain Stagg's projections were clearly subject to varying degrees of uncertainty. How many words, charts and maps were sufficient to enlighten the decision makers? How many were too many, encumbering the decision makers with data that would clutter their ability to make the best choice.

Staying with operational settings for the moment, John Keegan describes the different styles of order writing of the Duke of Wellington and U.S. Grant, but notes the effectiveness of both (Keegan, 1988). However, General Lew Wallace complains of receiving an ambiguous order from Grant's messenger at the Battle of Shiloh (Grant, 1885). Few would argue that these issues do not remain open and hotly debated: "How does a commander direct his subordinates without confusing them or sapping their initiative?".

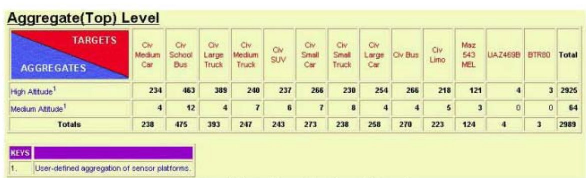
Given those operational issues, there is also a need to consider how computer-generated battle data are communicated to the participants in an exercise and how the insights from this evolution could be most effectively communicated to the analysts.

The earliest computer-generated simulations were often single platform/vehicle simulators, *e.g.* cockpit trainers and tank turret mock-ups.

**Figure 2 - Link Flight Trainer *circa* 1943 and KMW Tank Turret Trainer *circa* 2005 (Lowood, 2003 & KMW, 2014).**

Because of this trainee isolation, analyses of participant performance and training achievements were not too difficult. Late in the 20th century, efforts were made to link many of these individual platforms and "vehicles" together to provide interactive and team training.

This led to a desire to have even more constructive entities available via simulation (Messina, 1997b), an effort in which several of this paper's authors were intimately involved. Continued pressures for even more entities resulted in the further growth of simulations sizes (Gottschalk, 2010). These successes of consistently simulating more up to ten million entities created huge amounts of data (Yao, 2009). A single exercise could easily generate a terabyte of data, even after all "non-essential data" was discarded. Early attempts at visualizing the distilled simulation insights centered on tabularization of the data.


Aggregate(Top) Level

| TARGETS / AGGREGATES | Civ Medium Car | Civ School Bus | Civ Large Truck | Civ Medium Truck | Civ SUV | Civ Small Car | Civ Small Truck | Civ Large Car | Civ Bus | Civ Limo | Maz 543 MEL | UAZ469B | BTR80 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| High Altitude[1] | 234 | 463 | 389 | 240 | 237 | 266 | 230 | 254 | 266 | 218 | 121 | 4 | 3 | 2925 |
| Medium Altitude[1] | 4 | 12 | 4 | 7 | 6 | 7 | 8 | 4 | 4 | 5 | 3 | 0 | 0 | 64 |
| Totals | 238 | 475 | 393 | 247 | 243 | 273 | 238 | 258 | 270 | 223 | 124 | 4 | 3 | 2989 |

| KEYS | |
|---|---|
| 1. | User-defined aggregation of sensor platforms. |

**Figure 3 - Sensor Target Scoreboard from JFCOM Experiment (Graebener, 2003)**

While this was relatively easily programmed, it fails to convey in a graphic and easily grasped way the salient correlations that are important. Tabular data in particular, require time to contemplate and analyze. This is a luxury that may be available to small-scale simulation analysts and to officers in non-combat environments; however, it presents way too much data for effective analysis of mega-city simulations and imposes unacceptable burdens on officers experiencing the stress of combat. These hurdles to exploiting these computer augmented sources of data have been personally experienced by many in the simulation community. While these observations are still anecdotal, they appear to be so pervasive as to warrant the assertion that better visualization is mandated.

Other disciplines have attempted to provide more easily comprehended alternative projections of future events in a way that intuitively conveyed the range of futures considered likely. One of these is the creation and dissemination of what is colloquially referred to as meteorological "spaghetti charts" showing the potential paths of dangerous storms.

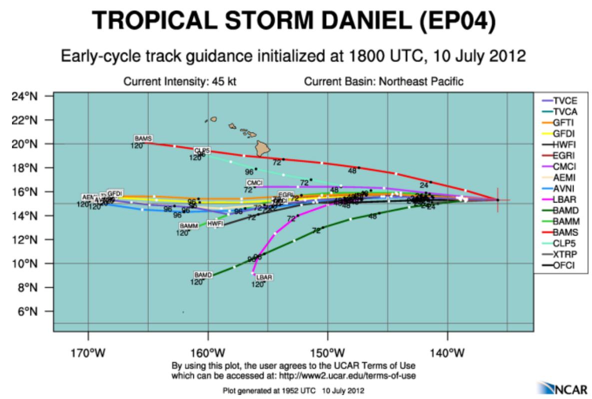



**Figure 4 – Hurricane track "Spaghetti Chart" (Cyclocane.com, 2104)**

## III. Challenges

One of the problems with the above type of data visualization is that it does not convey the historical, analytical or individual idiosyncrasies of each of the predicted tracks, something an experienced meteorologist might have developed over decades of professional practice. But, given the existence of such professional expertise, consider again the Stagg/Eisenhower situation. How do the technical experts convey the subtleties of their analyses to the commander without abrogating the commander's function of making the final decision? Perhaps more importantly, how often should they fully illuminate the issues, but either do not or cannot?

Another challenge is that of presenting the data in structured layers in a way that the commanders can invoke their own discretion as to how deeply they wish to probe the experts' analyses. Computers and hyper-text have created easy ways to present written data in printed text with easily selected links to more in-depth data, but even this poses a new challenge: that of deciding which data to put in the original text and which to make accessible via hyper-text links. The non-electronic analog to these issues is the traditional oral briefing by staff officers followed by questions from the briefed senior being the drill-down.

Voice tone and emphasis provide additional ways to convey certainty, importance, and relevance. Text and even computer-generated voice lack these refinements. When mission success and lives are at stake, every communication tool becomes more vital.

A third challenge is in representing multi-dimensional data via electronic means. While there are a number of immersive and 3-D display techniques available in the laboratory setting, the vast majority of analysts and commanders have only two-dimensional flat screens. A common technique is to represent this data in a "3-D format", but these do not always convey the insights from the material.

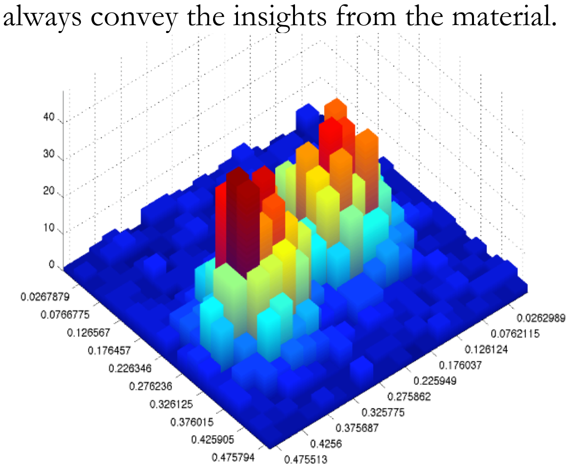



**Figure 5 - 3-D Histogram via Mat Lab (stackOverflow, 2014)**

In more advanced presentation, this type of chart can be rotated about all three axes for better viewing and analysis. But even on this issue, there often is the need to accurately and cogently represent dimensional data with four or more important dimensions.

Another challenge is the representation of analytic data on imagery or map displays of the geographic and structures features of the simulation or active battlespace, *e.g.* communicating an area of analyzed danger by outlining on a map display or shading on photographic imagery of the battlespace.

The last challenge to be mentioned here, is the one of individualizing content and presentation to the intended recipient. Good teachers, briefers and advocates all tailor their delivery to their audience based on pre-ascertained knowledge as well as observed body-language, attire, questions and other cues. Computers tend to have a unitary approach to communication. Were one to type in a topic at the Wikipedia search site, one would get the same article, no matter what your age, education, proclivities or interest. Entering "Quantum Mechanics": the first sentence reads, "Quantum mechanics (QM; also known as quantum physics, or quantum theory) is a fundamental branch of physics which deals with physical phenomena at nanoscopic scales where the action is on the order of the Planck constant."(Wikipedia, 2014). There is one other option known to a few: the Simple English Wikipedia, where the same search produces a first line of, "Quantum mechanics ('QM') is the part of physics that tells us how the things that make up atoms work."(Simple English Wikipedia, 2014). However, this requires foreknowledge of the choice and an affirmative act on the part of the data seeker. Both are good articles, no doubt, but directed at two different audiences: one comfortable with the Planck constant; one not so much.

## IV. Opportunities

In addition to the recognized challenges mentioned above, there are a number of opportunities to dramatically alter the way the information is presented to the warfighter. These are not seen as challenges by most users; they represent a new set of opportunities. Many of these are based on emerging technologies to be discussed below. In any case, they represent a vision of what can now be done to improve mission success and reduce casualties.

One of these opportunities is the recognition of and the tailoring to learning styles. There are two commonly recognized models for learning style differences, one posited by Kolb, the ELM model (Kolb, 1984) and one posited by Fleming, the VARK model (Fleming, 2014). Both models contain useful insights into the way humans acquire knowledge. While their work is couched in terms of academic instruction, their insights could be useful both in training and in disseminating operational knowledge.

Another opportunity lies in the area of individual personality differences. One would have been a poor senior commander in World War II to have issued the exact same order to each of the Generals MacArthur, Bradley and Patton and then expected the same responses by their respective commands. From the squad leader to the General of the Army, leadership depends on knowing how to get the best out of each individual. In producing information, be it analytical data for the simulation team or direction for the combat commander, computers now tend to generate the same output, no matter who the addressee. There are a number of ways that this issue could be addressed by a carefully designed program with both machine generated sensitivities and input from senior officers.

Due to limitations in computing assets and lack of familiarity with artificial intelligence (AI), simulations have heretofore relied largely on the slavish execution of doctrinal direction received by the various forces from their senior commanders. This is arguably even more troubling in asymmetric warfare, where there is no established doctrine and the opposing forces intentionally look for ways to circumvent defenses designed for more conventional forces. In addition, recent findings by the behavioral economists have highlighted the irrational application of reason by ostensibly rational human beings, (Ariely, 2010 & Kahneman, 2011). During one of the large-scale simulations at JFCOM (Lucas, 2003), one of the entity models was exhibiting unexpected and unusual behavior, so there was a discussion about making it behave rationally. At that point, one of the participants, having had some actual combat experience, quipped, "What makes you think humans behave rationally in combat?".

## V. Emerging Technologies

The focus is now on emerging technologies and techniques that may address the challenges and enable exploitation of the opportunities listed. These technologies and techniques are in varying stages of development and acceptance in many different disciplines. They all have been sufficiently validated to warrant a general interest in what they could contribute to the defense of the nation.

### Look-ahead simulation

Since the earliest days of battlefield simulation, there have been spirited discussions on the possibility of intelligent agent simulations being so valid and reliable that they could act as good predictors of potential outcomes on the live battlefield. Validity was not formally assessed at that time, but face validity was a bench-mark often applied. With an occasional disconcerting result like a flying tank model or a mark-time-marching deceased soldier avatar, even face validity eluded the simulation team from time to time. As both simulation techniques and computational science improved, the vision of a reliable predictive value from simulations gained credence. One of the efforts to which that led was the DARPA Deep Green initiative (Surdu, 2008). That project was designed to give enhanced views of combat situation awareness for use by commanders.

As the simulations upon which this vision relies are stochastic, there is a highly desirable

| Table 1. Proposed Uses of Quantum Annealing | | |
| --- | --- | --- |
| **Data Mgt.** | **Behaviors** | **Analysis** |
| Labeling Images | Extracting News Stories | Creating/ Testing Hypotheses |
| Scanning Data for Correlations or Anomalies | Natural Language Performance | Object Detecting in Imagery |
| Correlating Bio-Informatics | Factor Analysis of Intelligence | Verifying Computer Codes |

practice of running the simulation multiple times to observe and record the varying outcomes that are likely. Also impacting the utility of this technique is the issue of creativity of the combatant, as has been previously discussed. Doctrine only goes so far in controlling the actions of warfighters in combat. Some deviate intentionally and some do it mistakenly, but in both cases, the lack of adherence would call into question any simulation that ignores those contingencies.

### Quantum computing

One potential solution to the demands of running large-scale simulations for many iterations is the promise of quantum computing. Proposed in early theoretical papers by Nobel Laureate Richard Feynman, the use of quantum phenomena rather than electronic switches would present computer power heretofore unavailable to the computer scientists (Feynman, 1982). Adherents of this approach continue to be enthusiastic, saying things like: "… quantum computers could, in principle, be staggeringly powerful, taking just a few minutes to work out problems that would take an ordinary computer longer than the age of the universe to solve."(Lo, 2014). One of the features of quantum computing is its ability to assess several alternative states simultaneously.

Recent advances have made the use of this power seem increasingly imminent (Lanting, 2014). The D-Wave Quantum Annealer at the University of Southern California has been stable and productive and the larger machine (around a thousand Qubits) is expected in 2015, at which time some of the potentials of the technology may actually be realized (Lucas, 2013). Many of the classes of problems for which these speed-ups are projected are of interest to the simulation and intelligence communities.
(Lucas, 2013)

Even though they are still early in their development, quantum computers have demonstrated significant utility in areas of interest to the topics covered in this paper. There are some areas within the domain of computer generated forces (CGF) that are seen as having the greatest potential for significant advances in the overall performance of CGF systems. There still is significant work to be done in the development of the quantum computing systems and considerable ground that needs to be covered in both the conceptual approach to programming and in the orderly creation of a programmers' culture. The authors have seen this evolution in parallel programming for scientific clusters. While it may be several years before significant breakthroughs are readily available to the day-to-day DoD user, early recognition of the revolution this will accrue to the benefit of those who will be prepared for the future.

### Causal modeling

A new area of emphasis in simulation and modeling is causal modeling in which the focus is on causal factors, clearly a matter of interest to the intelligence analyst and the battlefield commander (Anthony, 2006). The computational aspects of this sub-discipline have been explored and advocated by well-regarded academics (Pearl, 2000). While computationally demanding, the programming paradigm is well described and application to large-scale battlespace simulation analysis should be straightforward. The benefits that can be expected from this implementation should include a heightened awareness within the analysts of the most important factors in the chain of causality, allowing both assurance of success on the part of the U.S. forces and suggesting the most efficacious interdiction of enemy forces (Brooks, 2006).

### Behavioral science insights

The fields of behavioral economics and game theory have effectively characterized some hitherto inexplicable reactions of decision-making by humans who are under stress. The behavioral science insights are directly applicable to the warfighters under consideration here. One of these is the ability to better realize a projection of human behavior based on even irrational choices, (Ariely, 2008), as further discussed below.

Other insights relate to the nature of nascent leadership in groups (Harvey, 1961) in which it was observed that leadership rose or fell on the appearance of meeting a societally perceived threat, even after that perception was debunked by subsequent experience. Leaders, once they were seen as failing to rise to a challenge that they personally saw as false, were abandoned by their alarmed followers. Surprisingly, the deposed leader were not reinstated, even after they were proven to be right and more sagacious. The study further showed that in an apparently combative environment, merely rallying two potential combatants to meet a new foe or mustering both sides to achieve a mutual goal could reduce antagonisms. These insights have historical precedents that are analogs, *e.g.* the rapid a frequent changing of allegiances during the Moorish *al-Andalus* period in Spain and the *Reconquista*. (Glick, 1979)

### Irrationality analysis

The field of behavioral economics has provided substantiation of irrational behaviors long observed by combat commanders (Ariely, 2011; Kahneman, 2011; and Gladwell, 2008). More saliently, Professor Ariely has focused on the predictability of even this irrationality. This provides an opportunity for behaviors to be observed, characterized and logged, both in the environment of the large-scale simulation and in actual combat operations. Unhampered by preconceived biases and consistent in analytic objectivity, the computer program can ferret out behavioral trends which would otherwise defy logic and escape serious consideration by humans.

Further, training of analysts and commanders alike can help to counteract the tendency to assume that friends and foes will act as anticipated. Care can be, and should be, taken to program systems not to extrapolate observed behaviors into dictates so invariable as to be misleading. Knowing the speed with which armies move, the Germans underestimated the time it would take General Paton to swing his Third Army North and relieve Bastogne. Again, the approach should be to convey the typical, with an additional graphical representation of the physically possible. The analysts and commanders need to be reminded that in the stress of battle, soldiers can do things thought impossible.

### Data visualization advances

Phil: Please give us a paragraph or two.

The field of visualization continues to grow in both applications and impact (Tegarden. 1999). The use of data visualization to help the commander and the analyst to better understand and grasp the importance of information so as to make optimal use of abstract and voluminous data, should be enabled by current and emerging technologies (Doleisch, 2003). But, as others observe, there is an open challenge here: how to optimally match the visualization approach to the specific issues confronting the defense personnel who are faced with the demanding choices of combat.

### Evolutionary Computing

While it has proven very useful in a number of areas (Fogel, 1995), evolutionary or genetic computing is nevertheless very under-utilized in battlespace simulation and analysis. Entity behaviors are typically based on doctrine or observed actions. They usually do not learn, morph, or evolve, which sets them apart from the humans for whom they are avatars. The command structures of most modern armies have been accused of training to fight the "last war," and the rapid advances in technology make this practice even more dangerous, hence, impermissible. Asymmetric warfare also heightens the hazards of not considering the complete range of possibilities of new strategies and tactics, *e.g.* flying commercial aircraft into tall buildings. Randomly seeded evolutionary computing may take both the commander and the analyst down roads they otherwise would never have conceived.

However, there are hurdles to this use. Evolutionary computing is based on treating data that is sparse and behaviors that are spare in order to run the sufficient numbers of iterations to get the benefits of evolution. With simulations of ten million entities, each with complex behaviors, implementation of evolutionary computing will require thoughtful, innovative and efficient program codes. A prenascent capability that may soon be available is the use of Quantum Computing to enable evolutionary modules to generate entity "learning"
in the simulation code base.

## VI. Conclusion

Since the history of combat was first written, the fog of what will happen, what is happening and what happened has contributed to the quandary for both commander and historian alike. New generations of sensor, new systems of data management and new channels of communications have often more overwhelmed than assisted in this quest. More for want of will than lack of technology, this condition persists today. The preceding sections have outlined where we were, where we are and where we may go, using the best that technology has to offer.

What certainly is lacking is sufficiency in human factors research, implementation efforts, focus on the warfighter, and careful review. Some technologies are productively implementable as this is written; some are emerging and will need time for testing and evaluation. All will need validation in their use in simulation and acceptance in the caldron of combat.

## VII. Author Biographies

**Philip Amburn** is an Adjunct Lecturer in the Computer Science Department of the University of Arizona. Prior to that, he was a Research Assistant Professor at Mississippi State University and also had taught as an Adjunct Faculty member at the Air Force Institute of Technology (AFIT). After AFIT, he worked at Wright-Patterson AFB in Ohio for SAIC as the Forces Modeling and Simulation on-site advisor in Programming Environment and Training for the High Performance Computing Modernization Program. His research interests are constructive and virtual simulation, interactive 3D graphics, and visualization. He retired as a Lieutenant Colonel from the United States Air Force. Dr. Amburn received a BS degree in Physics from Kansas State Teachers College, his MSCS degree from AFIT, and his Ph.D. degree in Computer Science from the University of North Carolina, Chapel Hill.

**Dan M. Davis** is a consultant for the Information Sciences Institute, University of Southern California, focusing on large-scale distributed DoD simulations. His service there was capped by his being the Director of the JESPP project for a decade. Earlier, as Assistant Director of the Center for Advanced Computing Research at Caltech, he managed Synthetic Forces Express, bringing HPC to DoD simulations. Prior experience includes serving as a Director at the Maui High Performance Computing Center and as a Software Engineer at the Jet Propulsion Laboratory and Martin Marietta. He has served as the Chairman of the Coalition of Academic Supercomputing Centers and has taught at the undergraduate and graduate levels. As early as 1971, Dan was writing programs in FORTRAN on one of Seymour Cray's CDC

6500's. He saw duty in Vietnam as a USMC Cryptologist and retired as a Commander, Cryptologic Specialty, U.S.N.R. He received B.A. and J.D. degrees from the University of Colorado in Boulder.

**Robert F. Lucas** is a Deputy Director of the Information Sciences Institute at the University of Southern California and leads the Computational Sciences Division. He is a Research Associate Professor in the USC Department of Computer Science. At ISI he manages research in computer architectures, VLSI, compilers, and other software tools. He was the principal investigator on the JESPP project from 2002 to 2011, which first implemented GPU acceleration in high performance computing for battlefield simulations. Prior to joining ISI, he did tours as the Director of High Performance Computing Research for NERSC at LBNL, the Deputy Director of DARPA's ITO, and a researcher at the Institute for Defense Analyses, supporting the National Security Agency. Dr. Lucas earned BS, MS, and PhD degrees in Electrical Engineering from Stanford University.

**Gene Wagenbreth** is a Systems Analyst for Parallel Processing at USC's ISI, doing research in the Computational Sciences Division. Prior positions have included Vice President and Chief Architect at Applied Parallel Research and Lead Programmer at Pacific Sierra Research, producing tools for distributed and shared memory parallelization of FORTRAN code. Gene has been programming for high performance computers since 1972. He has taught courses in GPGPU acceleration and lectures on parallel programming techniques at USC. He received a BS in Math/Computer Science from the University of Illinois.

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