IDA | Research Notes

THE WELCH AWARD 2015

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The Welch Award 2015

This issue of *IDA Research Notes* is dedicated to the winner and finalists of IDA's **Larry D. Welch Award** for best external publication. Named in honor of IDA former president and U.S. Air Force Chief of Staff, the award recognizes individuals who exemplify General Welch's high standards of analytic excellence through their external publication in peer-reviewed journals or other professional publications, including books and monographs. The articles in this edition are executive summaries of the original published pieces. We have identified and credited the original publication for each article and, where possible, we have included a link to the full piece.

Winner

In their article "Visible Signatures of Hypersonic Reentry," published in the *Journal of Spacecraft and Rockets*, April 2014, IDA researchers **Jeremy Teichman** and **Lee Hirsch** investigated the conditions for ground-level visibility and noticeability by the human eye of radiated light from aerothermal heating of hypersonic reentry vehicles. Aerothermal heating of hypersonic reentry bodies can generate significant radiation of visible light. The authors studied radiated visible light, transmission to ground level as a function of relative observer position, sky background contrast, human contrast perception limits, and psychophysical considerations for attention capture. Considering both pure ballistic trajectories and lifting-body trajectories, the article presents examples of spatial and temporal viewing zones for both detectability and noticeability. In some cases, viewing zones extend a significant distance from the impact location and/or include the impact location for a potentially significant period of time before impact.

Finalist

IDA Researchers **Thomas Johnson, Laura Freeman, Janice Hester,** and **Jonathan Bell** advanced the analytical state of the art of vulnerability testing relative to the practices that the Defense Department has followed for many years. Their article, "A Comparison of Ballistic Resistance Testing Techniques in the Department of Defense," was published in the *Institute of Electrical and Electronics Engineers (IEEE) Access*, December 2014.

Finalist

"A Technical Review of Software Defined Radios: Vision, Reality, and Current Status," published in the *Institute of Electrical and Electronics Engineers (IEEE) Military Communications Conference (MILCOM) Proceedings*, November 2014, by IDA Researchers **Lawrence Goeller** and **David Tate**, sets out the key issues that have prevented Software Defined Radios (SDRs) from achieving the vision of interoperability and forward compatibility, despite billions of dollars of investment in the Joint Tactical Radio System (JTRS).

Finalist

IDA Researcher **Eliza Johannes**, as lead author and subject matter expert for the article, "Analyzing Spatial Clustering and the Spatiotemporal Nature and Trends of HIV/AIDS Prevalence Using GIS: The Case of Malawi, 1994-2010," published in *BMC Infectious Diseases*, May 2014, developed—with outside co-authors Leo Zulu and Ezekiel Kalipeni—a situational framework for the general development and use of geospatial information for situational understanding and situational intelligence enabled by global and proliferating information and communications technologies.

The timely article, "Foreign Culture and its Effects on US Department of Defense Efforts to Train and Advise Foreign Security Forces," by IDA Researchers **Aaron Taliaferro, Wade Hinkle,** and **Alexander Gallo** was published in *Small Wars Journal*, November 2014. The authors' research offers a plausible explanation for why billions of dollars of military assistance did not produce a professional army capable of withstanding ISIS.

The *Iran-Iraq War: A Military and Strategic History*, a book by IDA Researcher **Kevin Woods** and former IDA Researcher **Williamson Murray**, draws from the captured Iraqi records available in the Conflict Records Research Center. The authors provide, in their book published by Cambridge University Press, 2014, new perspectives from the Iraqi point of view and an inside look at senior military decision making in that totalitarian regime.

In their article, "The Use of Probabilistic Plume Predictions for the Consequence Assessment of Atmospheric Releases of Hazardous Material," IDA Researcher **Nathan Platt** and **Jeffry Urban**, and outside co-author **William Kimball**, published in the *International Journal of Environment and Pollution*, 2014, the authors address an important and somewhat subtle issue in casualty assessment in a chemical release scenario.

IDA Researchers **Arun Maiya** and **Robert Rolfe** published their research on the problem of discovery from text, as opposed to only search—"Topic Similarity Networks: Visual Analytics for Large Document Sets"—in the *Proceedings of the 2014 Institute for Electrical and Electronics Engineers (IEEE) International Conference on Big Data.*

In their article, "U.S. Federal Investment in the Origin and Evolution of Additive Manufacturing: A Case Study of the National Science Foundation," published in *3D Printing and Additive Manufacturing Journal*, December 2014, IDA Researchers **Vanessa Peña** and **Bhavya Lal**, with coauthor Max Micali, analyzed the role that federal funding played in the development of the rapidly growing field of additive manufacturing, or 3-D printing technologies.

Visible Signatures of Hypersonic Reentry

Jeremy Teichman and Leon Hirsch

Winner

The Problem

Humans have observed glowing objects during atmospheric reentry for millennia, with some of the earliest known recordings of meteor showers dating to China in A.D. 36 (Imoto and Hasegawa 1958). The space age stimulated decades of scientific investigation of radiation during reentry of man-made objects (Maiden 1961). While state of the art observation is well documented, little quantitative analysis is available on the most rudimentary of capabilities—unaided human perception of these events. Our analysis explores whether, when, and where a reentry body will exhibit optical signatures visible to the unaided human eye.

Radiant Emissions

When an object moves through a gas faster than the speed of sound, it generates a shockwave. As gas passes through the shockwave, its pressure, density, and temperature suddenly rise. If the gas becomes sufficiently energetic, it will radiate electromagnetic energy with a wavelength and intensity related to its molecular content, density, and temperature. Aside from the gas, the reentry body's surface also heats up. The effects of surface heating and thermal conduction to internal structures influence applications such as hypersonic vehicles and reentry survivability (e.g., space shuttle tile damage). In our article, we restricted our analysis to the radiation from the impinging gas, which should be independent of the non-geometric qualities of the body.

The amount of radiation emitted depends upon the volume of the energized gas around the nose of the object. The integrated total visible spectrum radiant emission (luminous power) from the nose is approximately $\varphi = 0.1 J_S R^3_N$, where J_S is the volumetric luminous intensity at the stagnation point (scaling approximately as $\mathit{Velocity}^{8.5}\ \mathit{Density}^{1.6}$) and R_N is the nose radius of curvature (Martin 1966). As an example, a body traveling at 6-km/s velocity and 30-km altitude, with a 50-cm nose radius of curvature will radiate 125 kW of visible light, which is the equivalent of about 60,000 100-W incandescent bulbs.

For many conditions, particularly at night, reentry bodies could be noticeable for hundreds of kilometers around the impact point for periods of time ranging from tens of seconds to minutes before impact.

Atmospheric Optical Attenuation

Given the luminous power of the reentry body, how much luminous power reaches an observer on the ground?

The light radiated from the reentry body spreads, which reduces its flux in proportion to the distance squared, and attenuates exponentially through scattering and absorption in the atmosphere according to Lambert's Law (Brown 1965). The combined effect of these two principles is known as Allard's Law (Miller 1996),

$$E = \frac{\varphi}{4\pi D^2} e^{-\alpha_0 \frac{m}{m_0} H}, \tag{3}$$

where E is the illuminance (incident visible light flux) at the observer, D is the distance separating the reentry body and observer, α_0 is the attenuation coefficient, m is the air mass traversed along the line of sight between the observer and the reentry body, m_0 is the total air mass in the atmosphere along a vertical column from sea level to space, and H is the scale-height of the atmosphere over which density decreases by a factor of e (approximately 6,700 m). When viewing through the atmosphere, the viewing elevation angle, θ, has a pronounced effect. The air mass traversed when viewing at the horizon is 38 times greater than looking straight up at zenith (Young 1989). We derived the following expression of the air mass traversed for a given elevation angle:

$$\frac{m}{m_0} = \sqrt{\frac{\pi R_E}{2H}} e^{\frac{R_E \sin^2\theta}{2H}} \left(\operatorname{erf} \sqrt{\frac{z^2 + 2zR_E + R_E^2 \sin^2\theta}{2HR_E}} - \operatorname{erf} \frac{\sqrt{R_E} \sin\theta}{\sqrt{2H}} \right) \tag{4}$$

where R_E is the radius of the earth and z is the altitude of the object.

With Equation (3) we calculate how much illuminance, or total visible light flux, would reach a ground observer. From the observer's perspective, the reentry body's brightness or luminance depends upon both the illuminance and the amount of sky occupied by the reentry body. In other words, a very bright but small light source can provide as much illumination as a dim but very large source. This principle is easily observed on a long stretch of a city street that has traffic lights visible for multiple blocks ahead. Farther lights appear smaller, but their brightness appears undiminished. When a source is sufficiently far away, it appears as a point source (i.e., the minimum resolvable size). Beyond this distance, the illuminance still decreases with distance, but the apparent size remains constant, which causes the apparent luminance to decrease with distance. Apparent luminance is calculated using apparent angular size:

$$L = \frac{E}{\Omega_{Apparent}}, \tag{5}$$

where $\Omega_{Apparent}$ is the light source's size from the perspective of the observer. This is either the solid angle subtended or the minimum resolvable solid angle, whichever is larger.

Limits of Human Perception

The most basic determinant of whether an object is discernible by the unaided human eye is the object's contrast with the background. Contrast, C, is defined as the excess brightness of the object relative to the background luminance, L_0:

$$C = \frac{L - L_0}{L_0}. \tag{6}$$

An object brighter than the background presents positive contrast, while an object darker than the background presents negative contrast. The absolute value of contrast determines visibility so negative and positive contrasts of the same magnitude contribute equally to visibility (Gordon 1964). Positive contrast has no limit, whereas negative contrast cannot exceed a value of -1. The size of an object also contributes to its visibility, with larger objects being more visible. Below a critical angular size, objects appear as point sources, and size does not contribute directly to visibility. The third variable contributing to human visibility thresholds is ambient light level. Human eyes require greater contrast at lower ambient light levels. While the eye can discern a contrast of about 0.4 in daylight, it requires a contrast of about 710 in starlight. The critical angular size below which objects appear as point sources also grows with lower ambient light levels, ranging, from about 0.2 mrad in daylight to 2 mrad in starlight. Blackwell quantified the threshold contrast level as a function of object size and ambient light level (Blackwell 1946).

Noticeability

The examples above pertain to what humans will detect with careful study of the sky. This was not our motivation. Rather, our analysis sought to quantify what a casual observer would notice without cueing, foreknowledge, or viewing the sky at object's precise location. This phenomenon is termed "attention capture," (i.e., what people will notice). However, the literature's findings on this subject vary and depend upon many confounding factors such as the subject's task and state of mind, the dynamics and colors of the target, or background. (Simons 2001).

As a more widely accepted surrogate for noticeability under different conditions, our analyses adopted the Federal Aviation Administration (FAA) regulations for obstruction lighting on tall structures (to alert pilots of their presence and avoid collisions). For example, the FAA mandates obstruction lights of 100,000 candela luminous intensity to provide daytime visibility (noticeability) at 4.3 km on a day with 4.8-km meteorological visibility (U.S. Department of Transportation, Federal Aviation Administration 2007).

Applying Allard's Law with assumptions for background illumination and size of the light, we estimate a contrast value of 39 for FAA daytime obstruction lighting, compared to a threshold of 0.37; which leads to a contrast ratio of approximately 100x. The same can be done for the nighttime requirements to yield a contrast ratio of 200–400x. In both cases, the FAA lighting requirement is on the order of a few hundred times the minimum contrast threshold for detectability. We adopted a 400x threshold contrast level as the standard for high noticeability.

Results

Figure 1 displays noticeability of a reentry body at an instant in time. For a reentry body with a nose/leading-edge radius of curvature of 0.5 m, a velocity of 7 km/s, and an altitude of 50 km, the figure presents contrast level normalized to the threshold contrast level. A value of 1 indicates marginal detectability, and a value of 400 indicates noticeability equivalent to FAA standards for obstruction lights. Both of these levels

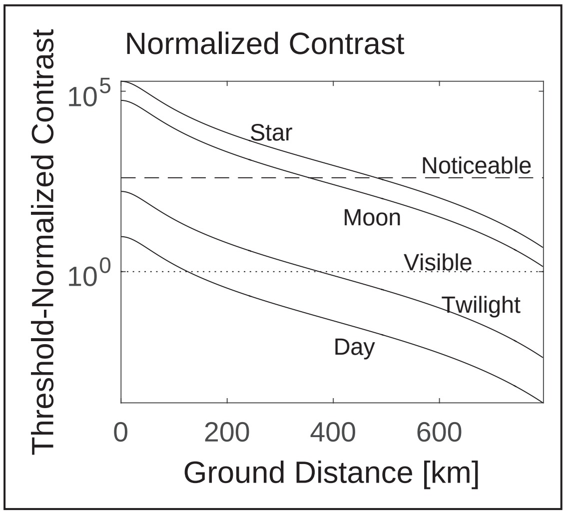

Figure 1. Metrics for Visibility

are indicated on the plot. The value of the metric is plotted over the ground distance of an observer from nadir below the reentry body. Curves are shown for four different ambient light adaptation levels: dark cloudless (moonless) night (labeled 'Star'), full moon night (labeled 'Moon'), zenith brightness at sunset (labeled 'Twilight'), and zenith brightness at 10:30 a.m. (labeled 'Day'), which represents a sun elevation angle of 60° (e.g., 10:30 a.m. in Washington, D.C., on July 21, 2009).

According to Figure 1, the reentry body would be noticeable at night at distances of nearly 500 km from nadir, even on a full moon night. During the day, however, the same reentry body would be detectable but not noticeable to the 400x threshold standard, even from directly below.

We next consider duration of noticeability for reentry bodies with different amounts of lift—ranging from purely ballistic (no lift) to gliding with a lift-to-drag ratio of 2. For each case, the reentry body possessed a nose radius of curvature of 0.5 m, a drag coefficient of 0.3, a diameter of 1 m, a mass of 1,000 kg, and initial velocity of 7 km/s. Simulations began at an altitude of 150 km (a point where atmospheric density becomes sufficiently high to generate visible signatures).

For the purely ballistic case, Figure 2 depicts periods of noticeability for different ambient lighting conditions. The center of the figure, marked zero distance downrange and crossrange denotes the point of impact. Ballistic reentry occurs quickly. With its brief time in the atmosphere confined to region about the point of impact, duration of noticeability is relatively brief, 20 seconds or less for all lighting conditions.

For the gliding case of Figure 3, the reentry body aerodynamically skips across the atmosphere multiple times. Eight pull-up cycles result in noticeability over 8,000 km up-range from the point of impact. Under daylight conditions, there is little opportunity to view the object at any point along the trajectory. Under dimmer lighting conditions, the object is visible for extended periods of time (over 2 minutes) uprange. Once the reentry body is within a few hundred kilometers from the point of impact, it has lost enough energy that it is no longer visible under any lighting conditions. Note, however, that due to the large ranges considered for this trajectory, lighting conditions would vary over this span of distances; the ground track of the 8,000 km aerodynamic portion spans about five time zones. In short, it could be nighttime at the first point of entry and twilight at the point of impact.

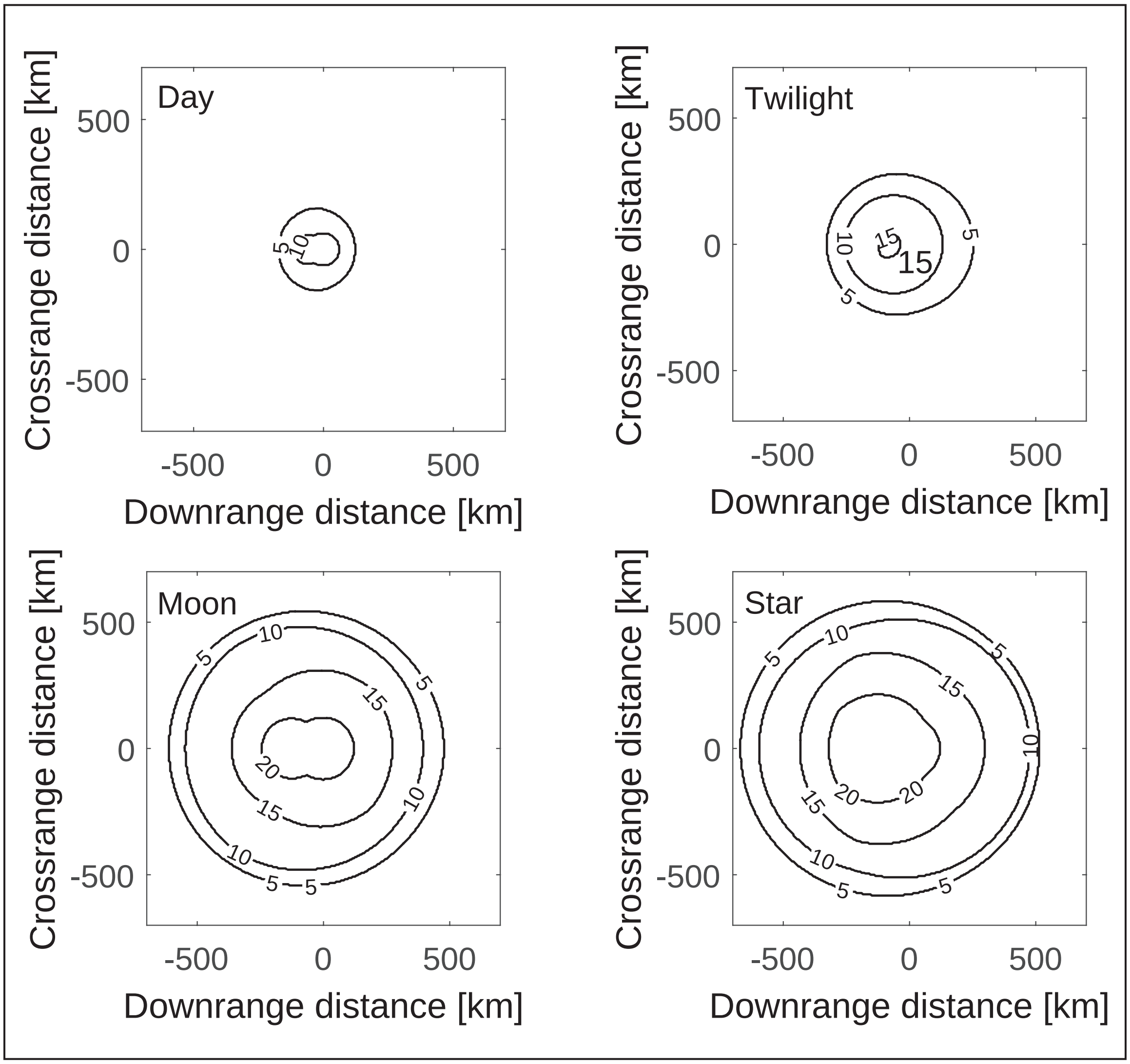

Figure 2. Duration of Noticeability [seconds], L/D = 0

Conclusion

For a given reentry body, we estimate the noticeability and visibility regions using criteria extrapolated from FAA lighting visibility requirements. For many conditions, particularly at night, reentry bodies could be noticeable for hundreds of kilometers around the impact point for periods of time ranging from tens of seconds to minutes before impact. Purely ballistic reentry bodies of the scale in the examples shown would be noticeable for hundreds of kilometers at night over regions including the impact point but for less than a minute prior to impact. Strongly lifting reentry bodies could be visible thousands of kilometers uprange of impact for over a minute as they skip off the denser atmosphere, but they would slow sufficiently with successive skips that, by the time they come over the impact point's horizon, they would no longer be noticeable.

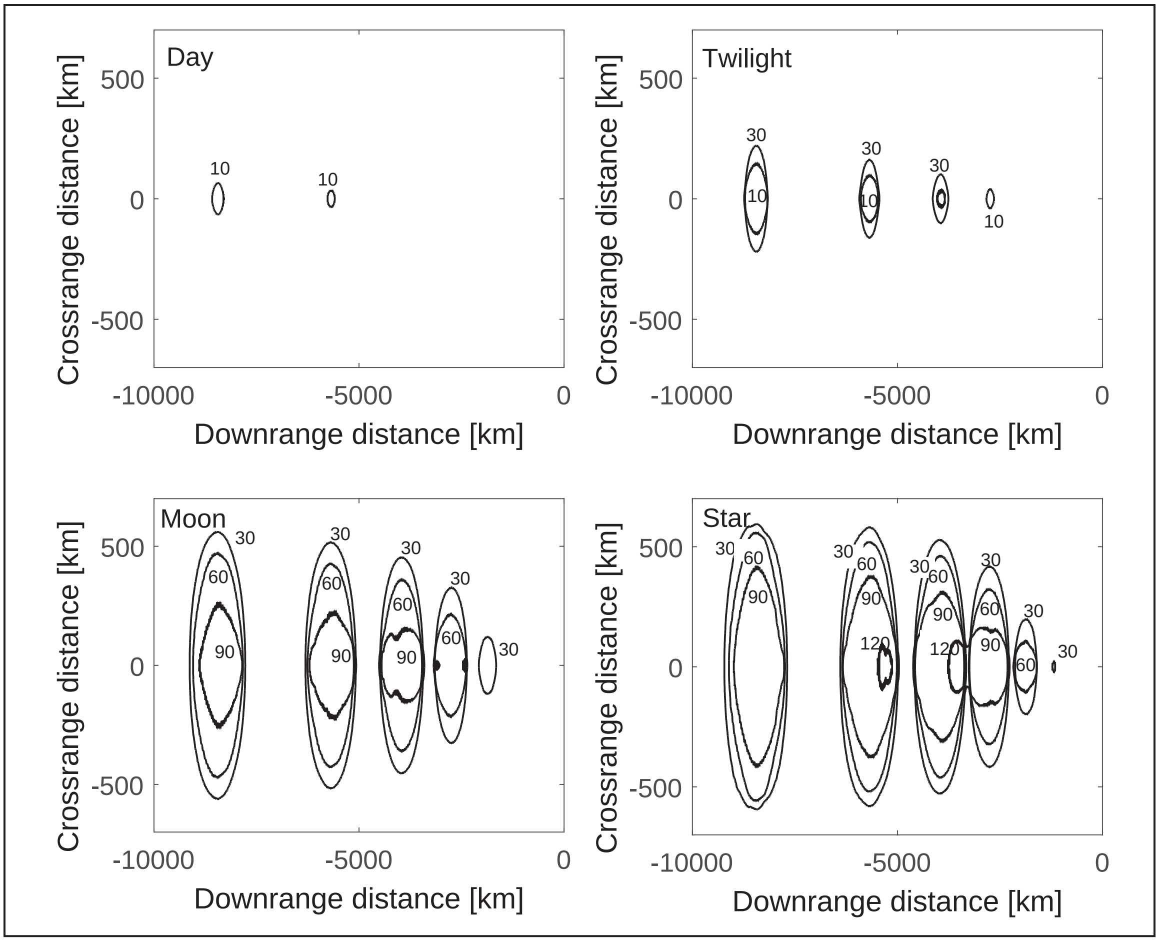

Figure 3. Duration of Noticeability [seconds], L/D = 2

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"Visible Signatures of Hypersonic Reentry"

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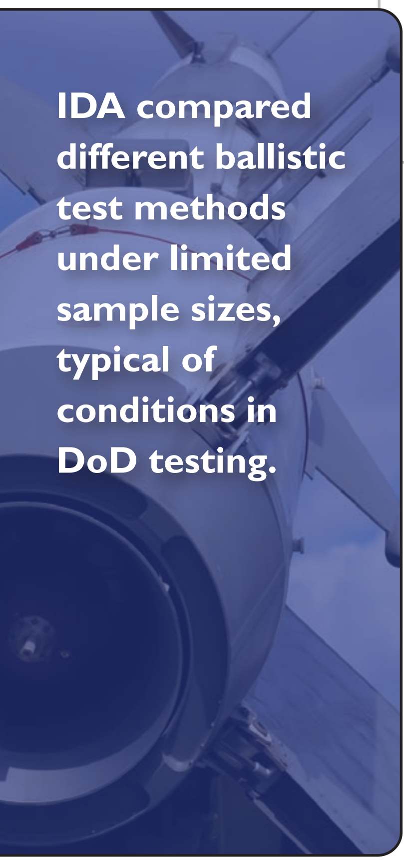
Ballistic Resistance Testing Techniques

Thomas Johnson, Laura Freeman, Janice Hester, Jonathan Bell

The Problem

The Department of Defense conducts ballistic resistance testing to estimate the probability that a projectile will perforate the armor of a system under test. Ballistic resistance testing routinely employs sensitivity experiment techniques in which sequential test designs are used to estimate armor performance. Statistical procedures used to estimate the ballistic resistance of armor in the DoD have remained relatively unchanged for decades. New test design methods can lead to improved testing efficiency, which is critical for test and evaluation in the current fiscal climate.



In reviewing sequential methods used in DoD and comparing them to those using Monte Carlo simulation, we found that newer test design and analysis techniques provide significant improvements over current methods. Newer methods can reduce test sizes, reduce bias in estimates, and support the estimation of the full probability of perforation curve instead of only a single metric.

Armor Testing

Various fields use sensitivity experiments to characterize the probability of a binary outcome as a function of a stimulus or stress. DoD ballistic characterization tests employ sensitivity experiments to characterize the probability of perforating armor or another material as a function of a projectile's velocity. One such example is shown in Figure 1.

Ballistic characterization tests, which are essential to understanding the vulnerability and lethality of military equipment, are conducted on systems ranging from body armor to vehicle and aircraft armor. In recent years, ballistic characterization tests were conducted for the Enhanced Small Arms Protection Inserts (body armor plates), the Enhanced Combat Helmet, the new floor paneling of the CH-47F, cockpit armor for the KC-46, and armor paneling of the Joint Light Tactical Vehicle, to name a few.

Ballistic testing is destructive, and DoD ballistic testing can be expensive in terms of both test and material costs. Sample sizes are generally limited, and ballistic characterization tests are almost always limited to fewer than 20 shots.

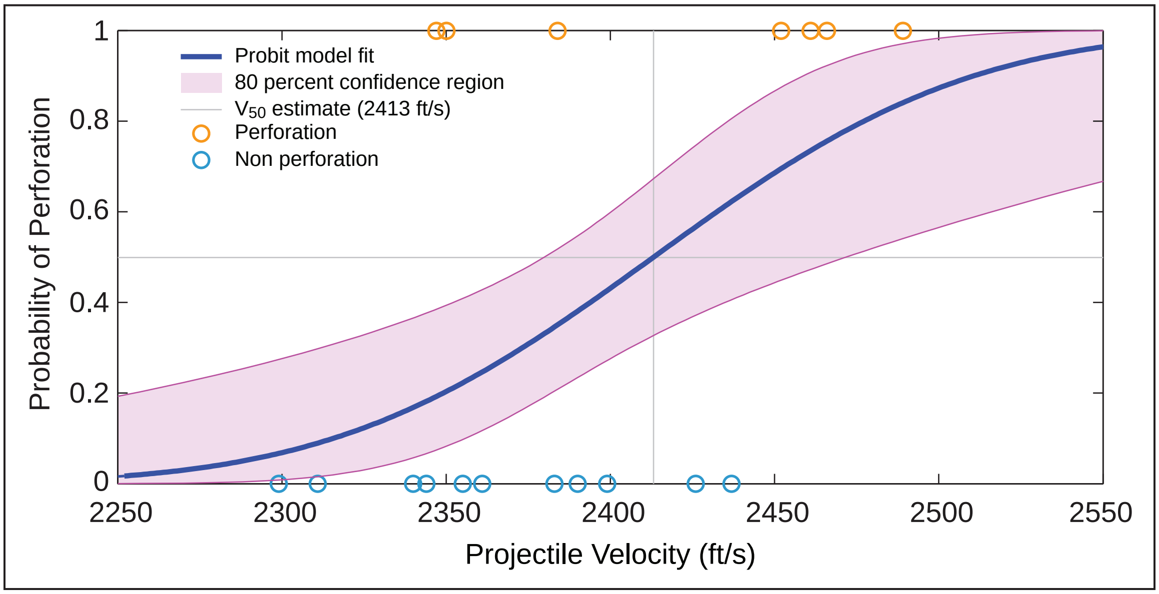


Figure 1. Example Data from a Ballistic Limit Test

Ballistic characterization testing frequently focuses on a specific percentile of interest and must therefore provide sufficient data to accurately estimate that percentile. The most common percentile of interest is the velocity at which the projectile has a 50 percent probability of perforating the armor—called the ballistic limit or V_{50} of the armor for the particular projectile (V_{50} Ballistic Test for Armor 1997). Historically, V_{50} was sufficient to characterize armor. It can also be estimated more precisely and with fewer shots than other percentiles. With modern armors, however, V_{50} might not be sufficient to characterize an armor; users might be more interested in the velocity at which the probability of perforation is 10 percent, or even lower. Estimating V_{10} is another reason to explore the efficiency of test techniques based on maximum likelihood estimation (MLE).

IDA compared different ballistic test methods under limited sample sizes, typical of conditions in DoD testing. Three simulation studies compared test methods in terms of their efficiency and accuracy at estimating V_{50} and V_{10}.

To estimate V_{50} and V_{10}, we used the probit maximum likelihood estimator (Probit-MLE). In a probit model, the response of an armor target to a ballistic projectile can be characterized as perforation or non-perforation. Let $y_i = 1$ or 0 denote the binary outcome of the ith shot, perforation or non-perforation, where $i = 1,2,3,\ldots,N$ are the first, second, third, and final shot, respectively. Let $F(x_i)$ denote the probability that $y_i = 1$ for the velocity of the ith shot. The location-scale probit model, which we used in our article to characterize the ballistic resistance of armor, is $F(x,\mu,\sigma) = \Phi((x-\mu)/\sigma)$, where Φ is the standard normal cumulative distribution function. We define x_P to be the Pth quantile of the distribution, where $F(x_P) = P$. In this formulation, μ, the estimator of V_{50}, is estimated using maximum likelihood estimation, and is referred to as the Probit-MLE estimator (Collins 2012).

Numerous aspects of a ballistic resistance test can affect the quality and consistency of the results: the laboratory setup, location of projectile impact, obliquity angle, temperature, and projectile type, among others. We focused on statistical aspects, namely, the sequential methods.

Sequential Methods

A sequential method dictates the velocity setting of each projectile fired in a test. We investigated seven sequential methods, chosen based on their prevalence in military armor testing, ease of implementation, and overall effectiveness at estimating V_{50} and V_{10}. The sequential methods compared are:

- Up and Down Method (UD) (Dixon and Mood 1948)
- Langlie Method (LM) (Langlie 1962)
- Delayed Robbins Monroe Method (DRM) (Hodges and Lehmann 1956)
- Wu's three-phased optimal design approach (3Pod) (Wu and Tian, Three-Phase Sequential Design for Sensitivity Experiments 2013)
- Neyer's Method (NM) (Neyer 1994)
- Robbins Monroe Joseph Method (RMJ) (Wu and Tian, Three-Phase Optimal Design of Sensitivity Experiments 2014)
- K-in-a-row (KR) (Gezmu 1996).

To illustrate their utility, Figure 2 shows notional tests for selected methods.

Simulation Comparison Study

We compared sequential methods, estimators, and stopping criteria using Monte Carlo simulation. We used a Probit model to represent the true relationship between probability of perforation and projectile velocity. We considered two sets of true parameters that are reflective of the combat helmet example shown in Figure 1: (1) μ_T = 2,400 ft/s, σ_T=75 ft/s, and (2) μ_T=2,400 ft/s, σ_T= 150 ft/s.

A simulated test is carried out in a manner similar to a physical one except that no projectiles are fired, and the outcome of whether the projectile perforated the armor is determined using a random Bernoulli draw from the probability of perforation estimated from the true model. For example, if a given simulated shot (x) is fired at 2,300 ft/s, according to the first set of true parameters, the probability that that projectile perforates the armor is $\Phi((x-\mu_T)/\sigma_T) = \Phi((2{,}300-2{,}400)/75) = 0.09$, where Φ is the cumulative distribution function from the normal distribution. Then, a random Bernoulli number is generated that has a 9 percent chance of being a perforation. To instill more realism into the simulation, we include a velocity set point error. For each calculated velocity, we add a random error drawn from a uniform distribution between plus or minus 10 ft/s.

The simulation employs a full factorial experiment to compare the different test designs in terms of their ability to estimate V_{50} and V_{10}. Table 1 shows the variables considered in the simulation experiment. Ideally, we hope to find a method that results

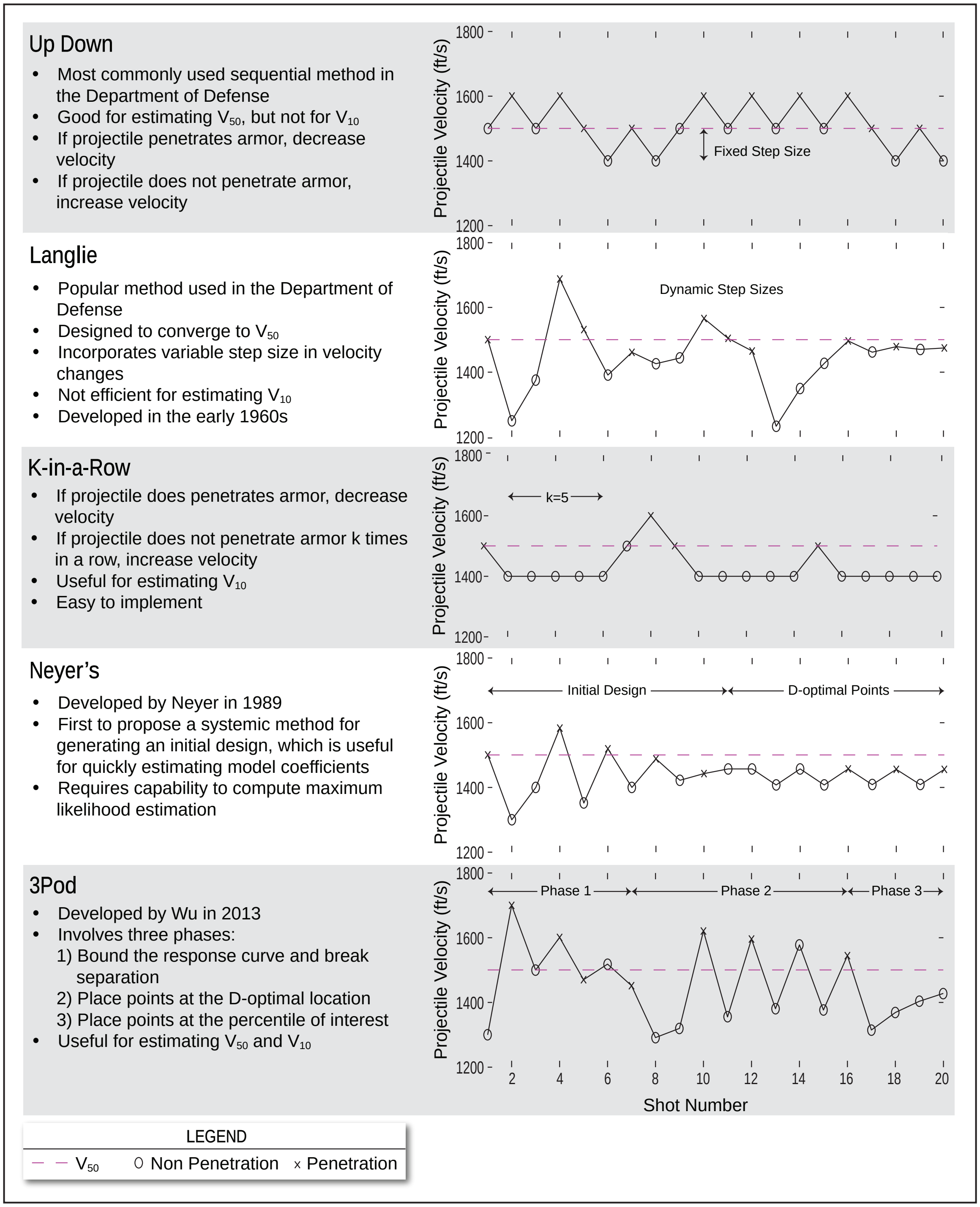


Figure 2. Example Tests for Sequential Methods

in improved estimates and is robust to poor starting estimates. Note that we intentionally consider cases where the mean and variance of the data are incorrect to represent test cases where there is poor understanding of the armors true performance. The response variables are the median and

Table 1. Factors and Levels

Sequential Method	Up and Down (UD), Langlie (LM), Delayed Robbins Monroe (DRM), Three Pod (3Pod), Neyer's (NM), Robbins Monroe Joseph (RMJ), K-in-a-row (KR)
Sample Size	N=20, N=40
σT	75 ft/s, 150 ft/s
σG/σT	1/3,1/2,2,3
μG	μT-2σT, μT, μT+2σT

interquartile range of the V_{50} and V_{10} bias.

The full factorial experiments consist of 336 trials. One thousand simulations are executed per trial. A simulation is representative of a single live fire test, consisting of either 20 or 40 sequentially fired projectiles. After each simulation, the V_{50} bias is calculated as the difference between the assumed "true" V_{50} and the V_{50} estimated from the simulation. V_{10} is calculated similarly. The median and interquartile range of the V_{50} and V_{10} bias are the response variables for each factorial trial.

Results

Figure 3 shows the median and interquartile range of the V_{50} and V_{10} errors from the 1,000 simulation runs. The figure illustrates that RMJ and DRM reduce the V_{10} median bias more than the other sequential methods. 3Pod is the next best performing, followed by KR, LM, NM, and finally UD. The advantage of reduced V_{10} bias by RMJ comes at the expense of V_{50} bias. Figure 3 also shows that the V_{10} median error is bias interaction between KR and σ_G when σ_G is equal to 2 in one direction for all methods except DRM and RMJ. This result occurs because the other sequential methods place runs closer to V_{50}, thereby biasing the V_{10} estimate closer to V_{50}. This result is magnified for LM, NM, and UD, since these sequential methods place runs closer to V_{50} by design.

Figure 4 shows the results of effect screening, which is a more robust way of understanding the results from Figure 3. Effect screening is an efficient way to summarize and compare the results of highly dimensional factorial experiments. The effects show the impacts of the factors, and interactions between factors, on the response variables. The effects are calculated by regressing each simulation outcome (median V_{50} and V_{10} error) on the factors of the factorial experiment. Coefficient estimates are shown for all main effects and two-factor interactions. The intercept of the regression model is the grand mean of the response variable, shown in the bottom left of the effects plot. The coefficient of a particular level of a factor describes the difference between the grand mean and the average response at that level.

Figure 4a shows that the effect that had the largest detrimental effect on the V_{10} error was the interaction between KR and σ_G when σ_G is equal to 2. In that case, KR is unable to converge

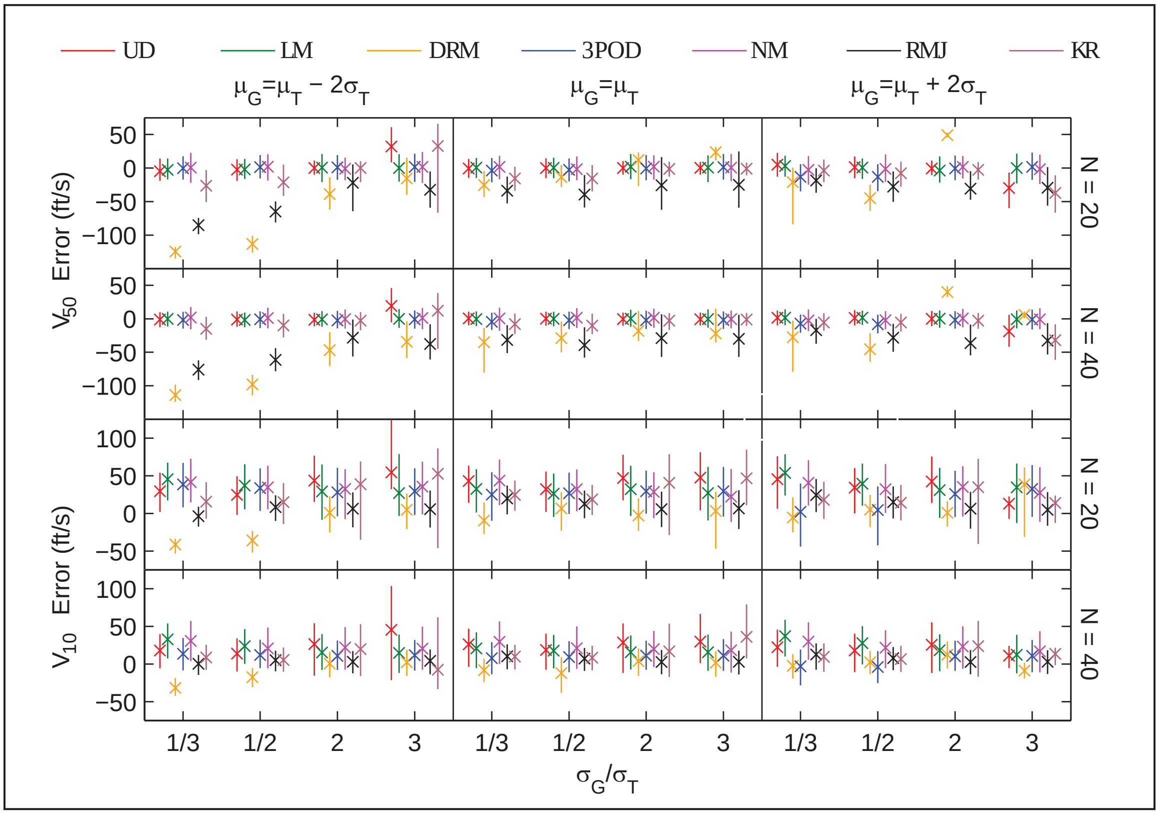


Figure 3. Simulation Outputs

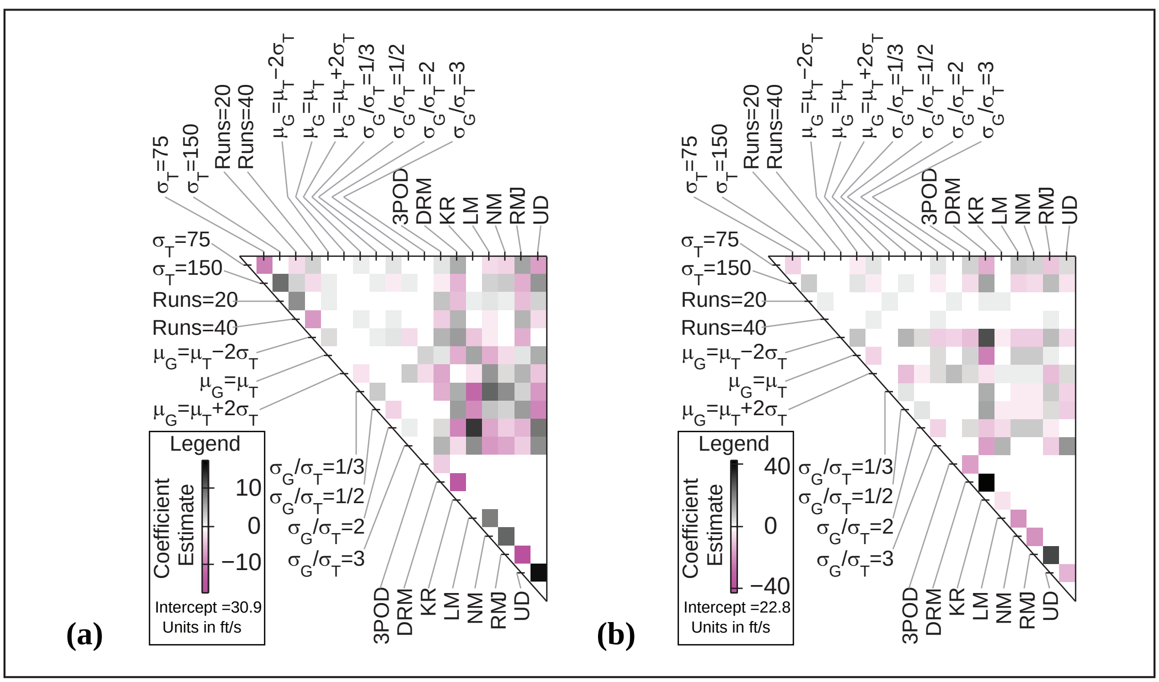


Figure 4. Screening Results for (a) Magnitude of Median V_{10} Error (b) Magnitude of Median V_{50} Error

to V_{10} because of its large step size. UD and KR seem to suffer estimation inaccuracies from interactions, more than the other sequential methods. Meanwhile, 3Pod and NM appear to be most robust.

Figure 4b shows that the three best sequential methods for reducing V_{50} bias are LM, NM, and 3Pod. RMJ and DRM yield the worst V_{50} bias. This result is not surprising because DRM and RMJ forgo initial designs and do not place points near V_{50}. Meanwhile, 3Pod and NM employ initial designs and D-optimal selection criteria that balance the design space.

In general, we found that the methods compared in this study perform commensurate with the goal of the test design. The top three sequential methods that reduce V_{10} bias are, in descending order, RMJ, DRM, and 3Pod. However, 3Pod is more robust to incorrectly specified values of μ_G and σ_G / σ_T than DRM. We also noted that DRM performs erratically for tests with greater than 20 samples because its step size becomes smaller than the velocity set point error. UD, LM, 3Pod, and NM resulted in the lowest bias on V_{50}. The 3Pod method appears to be the most robust method of estimating multiple quantiles.

Conclusions

The DoD uses sensitivity experiments to assess the ballistic resistance of various types of armor. We have shown that employing more recent sensitivity test design methods such as 3Pod and Neyer's Method can lead to improved testing efficiency, increased accuracy, and supports estimation of the entire response curve. Use of these new methods requires that the test community perform real-time statistical analysis of the data during test to select sequential test shots. We have also demonstrated the advantage of using maximum likelihood estimation and generalized linear models in the analysis and execution of ballistic limit testing. Maximum likelihood estimation techniques permit generation of the full perforation response curve, providing more information for the same test resources.

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Vision, Reality, and Future of Software Defined Radios

David M. Tate and Lawrence N. Goeller

The Problem

The DoD vision for how software defined radios would revolutionize future military communications had a number of goals:

- **Be able to communicate (voice or data) between any two radios, once configured**
- **Be upgradable to use future communications systems on existing hardware**
- **Provide new and continuously improving networking capabilities over time**
- **Reduce future development costs for new wireless capabilities**
- **Reduce future procurement costs for radio hardware through higher volumes and longer useful radio lives**
- **Reduce future maintenance costs for radio hardware through commonality**

Reaching these goals is not feasible with current or near-term technology.

The invention of the software defined radio (SDR) in the early 1990s made it seem possible for the Department of Defense (DoD) to replace incrementally more than 100,000 diverse and incompatible radios with more versatile and interoperable radios.

The idea was that waveform software[1] would run as "applications" on generic radio hardware that would perform the necessary physical radio functions (e.g., carrier generation, modulation, synthesis, and multiplexing) as directed by the software. The analogy would be to various possible apps that can run on the same tablet or cell phone. The waveform software would be *portable* to new hardware with a minimum of effort.

In the late 1990s, DoD completed several demonstration projects and prototypes that seemed to confirm the viability

[1] In general, a waveform is the time series of radio signals that encodes information and is transmitted from one radio to another. The SDR community uses the term more broadly, to refer to all of the processing steps that encode and decode the information transmitted for a given mode of communications. These include modulation, channel encoding, multiplexing, frequency hopping, and so forth.

of the SDR approach for military communications. Based on this, the Programmable Modular Communications System (PMCS) and Joint Tactical Radio System (JTRS) programs were launched and eventually merged under the JTRS label. The JTRS project was broken out into a number of separate programs—one for waveform software, one for Army vehicular radios, one for small form-factor radios, and so on. In the end, none of these programs delivered the envisioned capability of portable software that could run on multiple physical radios while delivering satisfactory operational performance.

The Director, Performance Assessment and Root Cause Analysis (PARCA) asked IDA to investigate the root causes behind this set of failed development programs. In particular, PARCA was interested in whether there were technical barriers to success that were not recognized at the time. The JTRS programs suffered from many confounding difficulties, including requirements changes, an awkward program structure and acquisition plan, and perverse contractor incentives. In addition to these, we were able to identify technical issues that alone would have been sufficient to prevent program success.

The problem has to do with the different kinds of hardware used to do computing. The original concept for portable SDR implicitly assumed that the software implementing any waveform would be executed on general purpose processors (GPPs) of the kind familiar to personal computer owners. GPPs are extremely flexible in the kinds of logic and computation they can implement, and can be programmed in high-level languages that allow the same code to run on many different machines. A standard—the Software Communications Architecture (SCA)—was developed to describe how the waveform software would interact with the hardware controlling the radio functions. The SCA specified two particular commercial middleware solutions: the Common Object Request Broker Architecture (CORBA) to mediate between software commands and radio function execution, and the Portable Operating System Interface (POSIX) application programming interface for real-time control requirements. Waveform developers would thus be able to write high-level programming language function calls that CORBA and POSIX would translate into hardware actions specific to the radio hardware being used.

As it turned out, current (and near-term foreseeable) GPPs simply could not provide the computational performance required to implement waveforms within the practical operating constraints of a military radio. The CORBA and POSIX calls add significant computational overhead to each action, so that powerful processors are needed to keep up with the real-time demands of radio frequency signal processing. Any processor powerful enough to achieve the needed performance could not meet the strict military limits on physical size and weight, heat generation, battery life, transmission range, and so forth.

In response to these difficulties, the hardware developers turned to Field-Programmable Gate Array (FPGA) technology as a compromise between the ease of coding and portability that GPPs would have provided and the performance requirements of the military radios. FPGAs are somewhat programmable (though less flexible than GPPs), but are faster and draw less power than GPPs. The hope was that this middle ground would allow the radios to meet both performance and form-factor requirements, while preserving some portability of waveform software.

Unfortunately, FPGAs proved not to be a "sweet spot" between GPPs and dedicated signal processing hardware of the sort used in legacy radios and cellular telephones. Even using the latest "system on a chip" generation of FPGAs, the radios were still generally unacceptable in range, weight, heat generation, and waveform performance. Adding to the problem, the SCA specification was not defined at a level detailed enough to guarantee compatibility with other hardware, or portability of FPGA code. The JTRS programs thus lost the benefits of easily porting waveform software from one platform to another, without solving the performance and form-factor issues.

In the end, SCA became part of the problem, rather than part of the solution. There is no current technology for which SCA is sufficient to ensure portability and achieve the necessary real-time performance for military wireless communications. On FPGA-based systems, requiring SCA software compliance hinders radio performance and increases waveform development costs, while providing no compensating benefits.

Even if computing power continues to increase exponentially according to "Moore's Law," it will be many years before GPPs will be small, fast, cheap, and efficient enough to support SCA-based SDR—and even then it will still be likely that computer hardware processing capabilities will continue to improve more quickly than software capabilities. In that case, it seems unlikely that anyone would want to install multiple generations of waveform software on the same piece of hardware, when the hardware will become obsolete more quickly than the software.

Having identified this fundamental barrier to the vision of SDR-enabled waveform portability, we propose a potential alternative approach that might recover some of the sought benefits. That approach uses a different analogy—instead of thinking of waveforms as being like software applications on a tablet or phone, think of them as hardware peripherals, like graphics cards or hard drives used by a personal computer. Graphics card capabilities change relatively rapidly, and it is not uncommon for high-end users (such as video editors or serious computer gamers) to change graphics cards several times before buying a new computer motherboard.

In this approach, the core radio hardware would be the "motherboard," overdesigned for the hardware capabilities available at its inception. The radio would provide a standard interface bus for radio function modules—analog-to-digital and digital-to-analog converters, power amplifiers, antennas, cryptographic processors, user interfaces, network routers, and (especially) waveform synthesizers. Two radios would become interoperable by plugging in the same waveform "card" (and the appropriate other modules). Modules would thus be portable and reusable, but could be replaced relatively cheaply as new and more capable versions were developed. The stressing processor functions for radio performance could be upgraded without buying a whole new radio. The standard for the radio interface bus would be open, but the workings of the individual radio function modules could be proprietary, with no loss of portability or interoperability.

Hardware continues to improve much more quickly than software. A modernization approach in which hardware would stay in service for years or decades, upgraded only via software, would contrast sharply with the path that consumer electronics have taken. A commitment to hardware interface standards and modularity might, however, allow DoD to realize at least some of the promise of the vision for military radios. In the meantime, the SCA has become a barrier to progress within the world of military wireless communications.

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Malawi, 1994-2010: Analyzing HIV/AIDS Trends Using Geographic Information Systems

Eliza Johannes

The Problem

Geospatial analytical methods, including geographic information systems (GIS), provide a critical method for understanding the nature and causes of spatial variation in HIV prevalence. GIS tools can enhance the ability to address public health problems and better inform the planning, implementation and assessment of interventions in affected areas. However, the utilization of GIS has been limited in sub-Saharan Africa in part due to scarcity of reliable spatially coded data. Malawi—one of the six low-income countries with the highest HIV prevalence rates globally—is the case study for this article.

The longer it took to travel to the nearest public transport, the higher the prevalence of HIV... Consequently, HIV prevalence decreased with mean distance from the main roads.

Malawi has made great strides in decreasing the number of HIV/AIDs victims. The 2012 global AIDS report ranked Malawi as one of 25 countries with declines of 50 percent or more in new cases of adult (aged 15 to 49) HIV infection globally. It is also among 32 countries to report a 25 to 49 percent decline in HIV deaths (2005-2011). Antiretroviral therapy also showed drastic improvement between 2001 and 2011. HIV prevalence, however, still presents a significant challenge (Nykiforuk and Flaman 2011).

An estimated 923,058 of Malawi's 14 million people were living with HIV/AIDS in 2010. Prevalence among sex workers was up to 70 percent, and nearly 600,000 children were orphaned as a result of HIV/AIDS. Disparities regarding who was affected and where were also glaringly apparent: HIV prevalence is more than 2 times higher among female than male youth aged 15 to 24 and almost 3 times higher among urban women than those in rural areas (22.7 percent versus 10.5 percent) (National AIDS Commission (NAC) 2011).

Spatial statistical tools were used to examine spatiotemporal trends in HIV prevalence between 1994 and 2010 and to identify and map the spatial variation/clustering of factors associated with HIV prevalence at the district level to determine "hotspots" and "coldspots" for potential targeting of interventions. HIV prevalence data for this analysis were gathered primarily from pregnant women attending antenatal clinics (ANCs).

Most GIS-based analyses of HIV/AIDS in Africa have largely been either at the coarse continental scale (which has limited national policy relevance) or at fine local scales requiring heavy data collection and having limited spatial scope. Despite increased use of such analyses in Africa, few have analyzed the spatiotemporal variation and clustering of HIV prevalence or its drivers at the lower (or meso) scales where such methods can improve understanding and enhance effectiveness of interventions. While analysis at this level can present challenges, ANC data are a good source of information and more readily available allowing for lower scale analysis. ANC data allow for longitudinal trend analysis and can be rescaled to district or other scales by using spatial interpolation techniques.

Drivers behind HIV epidemics are numerous and diverse and differ over time and space, making addressing such a public health problem challenging. In the case of sub-Saharan Africa, the proximate cause of the high incidences of HIV is well documented —unprotected sex with an infected person. However, recent research has shown that there are underlying drivers that merit more analysis to better combat the epidemic. These drivers include cultural, historical, socio-economic, demographic, and geographic factors—all of which contribute to the vulnerability of particular groups of women and men who engage in risky sexual behavior. For Malawi, identified underlying HIV drivers include low literacy, high poverty, gender inequity and low social and economic status of women, high rates of unprotected casual and transactional sex, and low male and female condom use, among others.

The 19 studied ANCs were particularly useful in that they provided a longitudinally rich network of surveillance material that was gathered from 1994 to 2010. The network nearly tripled in 2007 to 54 clinics although the original 19 were maintained for continuity and spatiotemporal analysis purposes. Data were collected annually from 1994 to 1999, then biennially, and included the latitude and longitude coordinates of the ANCs to allow for mapping. HIV prevalence rates were the only consistent data available for all years. Although this is considered a limited source of information, it remains the major source of HIV data in Malawi.

To determine spatial dependence in HIV prevalence, spatial interpolation, and spatiotemporal trends, HIV prevalence rates for pregnant women aged 15 to 49 were plotted. This allowed for a broad, multi-scalar, spatiotemporal perspective of HIV epidemics across the national, regional, urban, and rural levels. GIS tools such as ArcGIS desktop 10.0 empirically tested for spatial dependency in HIV prevalence at the national scale. The result was a continuous surface of HIV at 1x1 km spatial resolution generate prevalence estimates at the meso scale. This visualization enabled cluster/hotspot and regression analysis.

To produce a smooth surface for visualization and data generation at the district level, the Inverse Distance Weighted (IDW) spatial interpolation method was employed for the selected years. The variable setting of 6 to 10 points was used to predict values at each unknown location. GIS tools were then used to extract HIV estimates for the 31 "districts" (27 of Malawi's 28 districts and four main cities of Blantyre, Lilongwe, Zomba, and Mzuzu) by averaging prevalence values in constituent 1x1 spatial cells. Local measures of spatial association used within ArcGIS 10.0 allowed for "where the clusters or outliers are located" and "what type of spatial correlation is most important" (Tanser, et al. 2009). Anselin's Local Moran's I (Moran 1950) was employed to detect core clusters or outliers of districts with extreme HIV prevalence values not explained by random variation. These clusters were then classified into hotspots, coldspots, and spatial outliers.

Multiple regression analysis of HIV prevalence for 2010 determined and illustrated potential linkages of indicative drivers of observed spatial variation to particular hotspot/coldspot clusters of districts. Spatial distribution and clustering of selected factors were mapped. HIV prevalence per district among pregnant women attending ANCs served as the dependent variable. Multiple independent variables such as socio-demographic (e.g., education, poverty/wealth/consumption, and employment), HIV awareness and behavior, and geographic variables such as access to HIV related amenities were chosen based on literature and availability of the data at the district level. Thirty-seven independent variables were identified and subsequently narrowed down via a multi-stage statistical screening process in correlation analysis to 18 significant variables. A stepwise regression analysis further reduced the variable pool to 13.

The result of this analysis revealed several temporal and spatial trends in HIV prevalence at the national and regional scales. First, prevalence among pregnant women attending ANCs has significantly declined since the peak epidemic in 1999. Additionally, analysis revealed multiple geographically defined HIV "epidemics" with diverse spatiotemporal trends. The southern region consistently had the highest HIV prevalence—7.0 percent higher than the national prevalence (1996 and 2007). The northern region had the lowest but essentially merged with the central region's from 2003. Urban areas typically had higher and more severe epidemics whereas rural areas were less intense and slower/lower. Yet research revealed the intensity of these two epidemics has been converging from a 2.8-fold difference in 1995 to 1.5-fold by 2010.

Presence of a spatial structure was confirmed although there was significant temporal variation in spatial dependence including in the early years (1995, 1996, 1999). The HIV epidemic in prevalence and spatial extent intensified from 1994 to 1999 but declined from above 25 percent in 1999 to below 12.5 percent nationally by 2010. Spatial analysis revealed that core clusters of hotspots were present in much of the southern region. To determine potential drivers for HIV prevalence for 2010 and their local spatial patterns, Ordinary Least Squares (OLS) regression was used to produce four models. The fourth model was chosen as the "best" based on explanatory power and collinearity diagnostics.

The model revealed that the longer it took to travel to the nearest public transport, the higher the prevalence of HIV at the district level. Consequently, HIV prevalence decreased with mean distance from the main roads. These findings are consistent with other studies that have found an inverse relationship between HIV prevalence and distance to main roads. The only behavioral explanatory factor for HIV prevalence was the proportion of women who had ever taken an HIV test, which proved to be the second most influential factor and was positively associated with HIV prevalence. However, more nuanced analysis on HIV testing behavior determined that education was negatively correlated with HIV prevalence, suggesting that the more education pregnant women receive, the less likely they are to have HIV/AIDS and that some level of education is good for AIDS prevention.

This analysis utilizes GIS tools to challenge the logic and effectiveness of uniform policies and interventions given the unique circumstances of each area. It reveals that HIV epidemics are an aggregation of several spatially defined sub-epidemics (national, regional, urban, rural and local clusters) each of which demands its own specific and unique course of action given its context. One of the most prominent temporal trends to emerge was the general decline in HIV prevalence after the rise in 1999. This reflects Malawi's intense efforts to allocate human and financial resources to combat the epidemic. Another significant trend was the slow but developing spatial evening in HIV prevalence as the epidemic stabilized and declined after 1999. Cluster analysis revealing the southern region as an HIV epicenter was also a significant finding. The prevalence of HIV in the southern region could be due to its history of urbanization in addition to being the most densely populated, having the highest levels of rural poverty, and a prevalence of syphilis.

Our analysis revealed much with regard to analysis of spatial clustering and spatiotemporal trends of HIV/AIDS prevalence using GIS. However, there are limits to the study. More detailed analysis must be done to focus on local HIV variation at a finer spatial scales and the drivers of HIV incidence. Such research could better capture underlying factors of HIV prevalence such as HIV prevention knowledge, personal resources, and socio-economic access or exposure to health services to inform public health policy decisions. Additionally, further research could determine spatial limits of the spatial dependence of HIV on neighboring values at different spatial scales to better inform interventions among other aspects.

Our work represents one of the few spatially explicit longitudinal analyses of HIV prevalence to date though a growing number of researchers are attempting similar research. Acknowledging its limitations, our analysis demonstrates the need for more spatial analysis to understand the geographic nature of epidemics, examine trends, and use this knowledge for more targeted interventions to combat HIV/AIDS in affected regions.

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"Analyzing Spatial Clustering and the Spatiotemporal Nature and Trends of HIV/AIDS Prevalence Using GIS: The Case of Malawi, 1994-2010"

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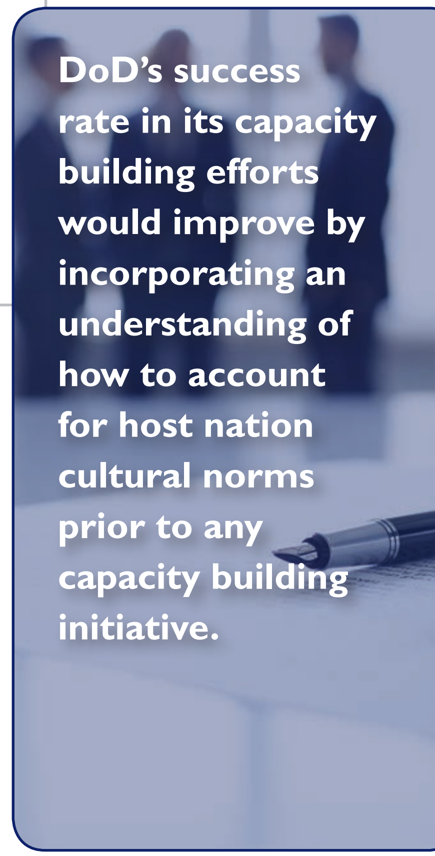
Effects of Culture on Training Foreign Security Forces

Aaron Taliaferro, Alexander O. Gallo, and Wade P. Hinkle

The Problem

Beginning just a few years after World War II with the passage of the Greece-Turkey Security Act of 1947, the DoD has been in the business of training and advising foreign security forces with the purpose of increasing their capacity to provide for their own security. However, DoD's approach to these efforts is largely premised on management theories grounded in Western cultural norms of interpersonal interaction—characteristics not present in the Near East, Central and Southeast Asia, or across the Maghreb and the Horn of Africa where post-9/11 U.S. Security sector assistance focuses. Further, the focus has been at the tactical level, which has proven to be unsustainable.



DoD's success rate in its capacity building efforts would improve by incorporating an understanding of how to account for host nation cultural norms prior to any capacity building initiative.

Within the 2006 Quadrennial Defense Review (QDR), the Department of Defense (DoD) formally pointed to the need to build partner capacity, a theme that is repeated in subsequent DoD strategy publications. The 2014 QDR notes that "capacity building is neither an easy nor short term task. Traditional solutions, such as pre-packaged, untailored seminars or courses paid for by IMET [International Military Education and Training] appropriations, do not build sustainable capability. Sustainability requires the foreign partner to have institutions able to manage acquisition of material, arrange logistics services and manage human resources."

To build partner institutional capacity, DoD sponsors several Defense Institution Building (DIB) programs. To be successful, these programs require a tailored and patient approach to the cultural norms of the partner nation—something not frequently addressed by DoD practitioners.

Why Institutional Capacity Matters and How It Relates to Culture

In general, the biggest gaps at the institutional level are weak planning processes. Defense planners must identify, prioritize, fund, and sustain military capability within national budgetary structures. In Western culture, our planning processes tend to focus on points of disagreement, which empower stakeholders to arrive at consensus-based decisions. However, we have not encountered such processes in many non-Western nations. Rather, those decision-making processes avoid open deliberation of points of disagreement and process participants are not incentivized to make consensus-based decisions.

A case in point is the U.S.-funded and -installed Afghan Human Resources Information Management System (AHRIMS). The purpose of this automated information system for recording and archiving personnel information was to improve existing Afghan personnel management practices that rely on paper records. However, the system not only was unsustainable from a technical standpoint, it was also a cultural mismatch. As a result, the Afghans do not use the system. Rather they revert to paper processes with which they are more familiar. Why? For one reason, Afghan considerations, such as ethnically balancing the force—something AHRIMS was not designed to track or measure—trumped the Western norm of hiring and promoting based on a stratified ranking of merit.

DIB Must Apply Change Management Principles in a Culturally Relevant Way

A recent RAND report assessed the effectiveness of the Warsaw Initiative Fund (WIF) program, a DoD capacity building program, at building defense institutional capacity in the Balkans, the South Caucasus, and Central Asia. The report found that WIF was moderately to slightly effective in the Balkans and the Caucasus, but ineffective in Central Asia because of the tribal loyalties that dilute a government's ability to manage using Western models of organization and governance (Perry, et al. 2013).

The RAND report alludes to something we have also observed as practitioners. Foreign culture presents barriers to the success of capacity building efforts; these barriers must be accounted for prior to engagement. Just because a nation's defense leaders agree to an offer of assistance from the United States does not mean they intend to embrace the advice. Americans, due to their cultural norms, tend to confuse what is deference by a foreign counterpart at the start of an effort with agreement, which results only in temporary, unsustainable change. This is especially true for U.S.-funded engagements.

Daryl Conner, of the Center for Leadership Studies, identifies what practitioners should avoid during a capacity-building engagement (Conner 2012):

- Being so eager to help with implementation that clients might be left without the will to take charge upon the practitioner's departure.
- Making a project appear easier, less manpower-intensive, and less complicated to the client than it actually will be.
- Solving problems instead of transferring skill to their counterparts.
- Focusing too much on what to do instead of how to think.
- Allowing clients to think they can change behaviors without changing mindsets.

- Personally taking on responsibilities that are the chore of the client's staff.
- Catering to the desires of the client personnel with whom the practitioner works instead of the leaders who sponsor the project.

Consistent with Mr. Conner's findings, Peter Morgan, of the United Nations Development Program (UNDP), notes that capacity development efforts frequently become "a problem rather than a solution." Technical assistance can crowd out local initiative and create dependence by host nations on new structures and systems implemented by foreign practitioners (Morgan 2002). Also, foreign technical assistance projects might be accepted by host nations in fearing that other kinds of aid would be denied if they declined. The UNDP report acknowledges Botswana's positive reform example, which included realistic time frames for project completion, strong host country leadership overcoming inertia, and country "ownership" of the reform (Banerjee, Valdiva and Mkandla 2002). Columbia University researchers found "ownership" to be highly relevant to the success of capacity building projects, which boils down to a simple thought: who requested the engagement in the first place (Engebretson, et al. 2011)?

Finally, we observe, and the development community agrees, that greater use of short-term technical cooperation personnel through multiple, short visits, paired with local staff who learn and implement a reform, leads to a greater chance of a successful capacity building effort—rather than a direct delivery of a process or system (Danielson, Hoebrink and Mongula 2002).

What Is Culture and How Does It Affect Capacity Building Efforts?

Institutions whose norms are different, even if the nation's government structures, technology base, and human technical capacity are similar, may not accept solutions and concepts that rest on Western norms. For example, in the West, conflict tends to be resolved openly and through general consensus. In Asian society, open conflict is avoided. Leadership dynamics are also different. In non-Western environments decisions are not easily questioned by subordinates, even if those subordinates reach a different conclusion using a participative decision-making process. Even if leadership buy-in is obtained, there may be informal leadership or loyalty networks that mitigate the power. Another Western cultural norm is the acceptance of winners and losers. In other cultures, solutions where "everyone wins," or at least no one's reputation is sullied as a result, may be more readily accepted.

Integrating cultural knowledge into a capacity-building engagement requires planning and constant awareness. Gerald Heuett, a corporate trainer based in Asia, points to three things that must be factored simultaneously. First, if deference to leadership is strong within the culture, engagements and methodologies should be introduced into the organization through its leadership, not an outside body. Changes should be credited to leadership and not outsiders. Conclusions of a new decision-making tool or process should focus on considerations instead of answers, for leaders to maintain credibility while accepting solutions generated by a foreign process. Second, in a culture that values relationship-based interaction, a proper staff must be in place; if a culture values harmony, any new decision must not create points of conflict. Third, thought must be given to whether a culture values group or individual initiative and permit processes to work accordingly (Hewett 2001).

Characteristics of Advisors Who Seek to Build Capacity in Foreign Institutions

Shekhar Singh, of the UNDP, wrote that capacity retention is not achieved by seminars and workshops that communicate common problems and solutions. Rather, deciding what to do and how to execute requires a capacity many client countries lack. Singh also notes that "experts" from the West are usually selected based on their subject matter knowledge, not on their ability to impart their knowledge to others (Singh 2002). From our view, technical experts without good consulting skills are not likely to be effective; however, a good consultant, with the right technical information, may be effective. Also key is balancing global standards with national needs in order to tailor the best practices of technical assistance to fit within the existing processes of a given country, even if existing processes are weak (Engebretson, et al. 2011). A Columbia University report found the extent to which advice can be communicated to and adapted by [foreign] counterparts is determinative in the success of institution building initiatives and requires advisors who are culturally competent.

Seeking to improve the effectiveness of its overseas technical assistance personnel, a 1981 Canadian study (Hawes and Kealey 1981) aimed to derive metrics by which to select and train personnel for projects in developing countries. Sponsored by the Canadian International Development Agency, the analysis surveyed and studied 160 Canadian technical advisors on 26 projects in six countries and 90 host country nationals. Interestingly, host country nationals viewed the effectiveness of assistance as a function of only two factors: intercultural interaction both socially and in the office (which led to a transfer of skill), and the degree of personal adjustment of the practitioner to the local environment. Strong interpersonal skills were the only consistent and significant factor in successful projects.

Conclusion—A Practitioner's View

DoD's limited experience[1] in executing DIB programs mirrors the trends of the development community as a whole. The approach to capacity building seeks a balance between the introduction of modern analytical tools and decision-making processes and the ability of host nation

[1] Our observation does not include the efforts at institution building undertaken in Iraq or Afghanistan under the auspices of Multi-National Security Transition Command–Iraq and Combined Security Transitional Command–Afghanistan. These are not DIB efforts sponsored by OSD DIB program funds.

organizations to utilize them given their technical limitation or cultural constraints. Therefore, early in an engagement, we rarely instruct host nations to make significant changes to their organizational structure or processes. Instead, we focus on strengthening existing processes such that new information or analytic visibility is available to leadership through current channels. By creating opportunities to see success from small changes, we have found leaders more likely to engage and support broader changes.

Instead of single-occasion seminars or classroom engagements, our visits over the course of a planned DIB effort last from one to two weeks and recur every six to twelve weeks for the duration of a project, which can be three years or more. The time on the ground during an engagement and the time between engagements is a joint decision arrived at by host nation leadership, the DoD sponsor, and the practitioners, and is largely based upon the availability and absorptive capacity of the host nation. We try to best balance how to be 'part of the team' in a classic consultancy role without falling into the trap of building or executing solutions on our own.

However, we encounter very few other DoD programs in the field calibrated to the cultural factors discussed here. We suspect that DoD's success rate in its capacity building efforts would improve by incorporating an understanding of how to account for host nation cultural norms prior to any capacity building initiative. The literature on cultural norms strongly suggests that we "western" advisors need to become more self-conscious about the degree to which our conceptualization of analytically based management is bound to our culture and not universally applicable. Further, an increased understanding would also allow DoD program managers to better select individuals for capacity building assignments.

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Military and Strategic Perspectives of the Iran-Iraq War

Williamson Murray and Kevin M. Woods

The Problem

Strategic realities and long-standing national interests all but ensure that the United States will find its military forces involved in the Middle East into the forseeable future. One way to prepare for an uncertain future is to develop a deeper understanding of the relevant past. The legacy of the Iran-Iraq War had a profound impact on the region. Issues of brutal dictatorial regimes, revolutionary religious zeal, deep sectartian divides, complex alliances, the risk of a wider war, all find their contemporary roots in the bloody inconclusive eight-year war that began in 1980. A window into the military and strategic decision making of the Iran-Iraq War can provide insights into the perspectives and world view of regional decision makers still shaping an unfolding future.

If the peoples of the modern Middle East managed to absorb only a smattering of the Western way of war, it was due largely to their contemporary experience with European military institutions, either as "the colonized" or being on the receiving end of Western military power.

In the eight-year-long Iran-Iraq War, Saddam Hussein and Ayatollah Ruhollah Khomeini, who held deeply opposed world views, struggled for dominance in the region. During the conflict, the opposing sides inflicted hundreds of thousands of casualties on each other. The two opposing leaders of the two states had ambitions greater than their national borders. For his part, Saddam and his Ba'athist colleagues calculated that victory over Iran would be the first step to leading the Arab world and creating an Arab superpower (Woods, et al. 2006). Khomeini, on the other hand, believed victory over Iraq would begin "exporting our revolution to the world." (Khomeini 1980)

In retrospect, both failed the basic tests of strategic competence. Both began the conflict apparently believing that emotion and simplistic rhetoric could motivate the masses to victory. When that didn't work, their response was to simply shovel more men and more resources into the struggle, while issuing ever more fanatical and ferocious pronouncements. Neither side proved competent to apply the most rudimentary ends-ways-means test to its approach to the war. The result was a bloody, inconclusive struggle that at times appeared to have no possible ending except the collapse of one or both of the contesting regimes.

That Iraq made the battlefield even more gruesome by introducing poison gas, not used extensively in a major war since Mussolini's invasion of Ethiopia in 1935, shows the pervasive desperation and hatred. Even more remarkable was Saddam's decision to use poison gas against a rebellious segment of Iraq's own population. Similarly heartless, the

Iranians deftly merged notions of religious martyrdom including symbolic "keys to heaven" with patriotic fervor to send 12- to 17-year-old boys to clear minefields. As though no one had learned anything from World War I, a favorite tactic of the *Pasdaran* and *Basij*, Iran's revolutionary militias, was to launch human-wave assaults into the face of prepared Iraqi defenses. Both sides left few laws of humanity intact. Perhaps the best explanation for the war's character was that it was about quarrels ancient and modern, political and religious. By the time the war ended, both sides had fired ballistic missiles—with only slightly better accuracy than the V-2s the Nazis fired during World War II—at cities of the opposing side. There is the very real possibility that, had one or both sides possessed nuclear weapons, they would have used them.

Militarily, there were no decisive victories. At the beginning, neither side proved capable of applying coherent tactics to the battlefield, or even operational concepts or strategic thinking. Initially, fanatical political and religious amateurs determined the disposition of forces and conduct of operations. During the war's course, military effectiveness at the tactical level improved somewhat, especially on the Iraqi side. While military professionalism slowly crept back into the picture in Baghdad, it never entirely replaced Saddam's amateurish decision-making; he alone made the significant military decisions. On the other side, military professionalism was rarely evident. Until the end of the war in July 1988, Saddam and Khomeini both equated some degree of military effectiveness with the casualty rates their forces suffered.

Nevertheless, the war's duration, as well its casualties forced both Iraq and Iran to adapt and learn. How and what they learned suggests much about how difficult it is to learn in the midst of a war, for which neither side was intellectually prepared. Once again, the conflict underlined that cognitive factors, such as initiative and military professionalism, were of greater consequence on the battlefield than mere muscle and technology. Iran's performance during the war also suggested the lengths to which human beings are willing to go on fighting for a cause in which they fanatically believe.

Equally important in evaluating Iraq's performance in the war from Saddam's perspective is the issue of military effectiveness. An important study on that subject focuses largely on evaluating specific areas of military competence, i.e., unit cohesion, generalship, tactical sophistication, information management, technical skills, logistics, morale, and training (Pollack 2002). However, such an approach poses problems because it rests largely on Western concepts of military effectiveness. For Western military analysts, the concept of military effectiveness seems to be relatively straightforward (Millett and Murray 2010). In the West—at least since the military revolution of the 17th century, which brought civil and military discipline to Europe's armies—states and their political leaders have taken for granted that military institutions would remain loyal to and supportive of the political structure.

As a result, Western military institutions have been able to concentrate largely on dealing with the external enemy, which has pushed the development of new technologies, doctrinal concepts, and more effective means of projecting military power on the battlefield and over great distances. Thus, the criteria for effective military organizations have come almost entirely to rest on their ability, proven in war, to destroy the state's external enemies.

Arab militaries began their descent in the seventeenth century from their historic and relative heights and continued through the final collapse of the moribund Ottoman Empire at the beginning of the twentieth. If the peoples of the modern Middle East managed to absorb only a smattering of the Western way of war, it was due largely to their contemporary experience with European military institutions, either as "the colonized" or being on the receiving end of Western military power. The result was that Arab military culture devolved into an echo of its former self, resting on a complex mix of myths and notions of bravery, tribal loyalty, raiding parties, and martyrdom that were, in many ways, indifferent to the effectiveness model inherent in the accoutrements and models of Western militaries. Such attributes have made Arabs extraordinarily brave warriors throughout the ages, but relatively poor soldiers in the context of wars since the nineteenth century.

As Iraq's ruler in 1980, Saddam subscribed fully to the myths of his culture. His aggressive efforts to fashion a common "Mesopotamian" culture to bind Iraq's multi-ethnic-multi-sectarian society under the Ba'ath in the late 1970s culminated at the beginning of the Iran-Iraq War. According to the often crude attempts to rewrite history, not only did Saddam portray himself as the "paramount shaykh" of a tribal culture, but, in defending the collective Arabs against their historic Persian foe, he had become "a leader who was victorious according to God's will" (Davis 2005) and (Baram 1991). He would have been entirely contemptuous of George Patton's famous remark that the business of war is not to die for your country, but to make the other bastard die for his. In the largest sense, Saddam's problem was embedded in the nature and the legitimacy of Iraq's political institutions.

Secular governance in the Middle East has historically rested on power, particularly military power, rather than on political theory, laws, and a generally accepted legitimacy of the state. A story is told that on his deathbed, the first caliph of the Umayyad dynasty told his son that "in order to keep the people of Iraq quiet, it was essential to give them a new governor every time they wanted one, however frequently" (Tarbush 1982). It seems that the purpose of the military (Iraq's most representative institution) was defined long before the state came into being.

For Saddam, the question his regime's legitimacy created not only a political problem, resulting in his ruthless purge of the Ba'ath Party in 1979, but a military one. Saddam knew well that the army was the one institution that could overthrow the Ba'ath regime, as it had done in

1963. In fact, since Iraq had emerged from the British mandate in the early 1930s, the legitimacy of its various governments had been anything but secure, while the army had displayed an enthusiastic willingness to overthrow the government of the day. Thus, as so many dictators have done throughout history, Saddam aimed to fully co-opt and, failing that, defang the only Iraqi institution with the independence and power to overthrow his regime.

From his perspective, the ideal senior commanders were those whom he could point in the general direction of the enemy, and who then, by their toughness and bravery, could destroy the external enemies of his regime. In terms of maintaining his control in Iraq, such an approach was certainly successful. Like Stalin, he had no qualms with bludgeoning his internal enemies via a minimum of effort and maximum of ruthlessness, while ensuring that the Army lacked the kinds of leaders who could launch a coup. Thus, in September 1980 on the eve of a war that would require a very different type of military, Saddam had every reason to believe that he and the Ba'ath party had created military institutions effective the way he wanted them to be (al-Marashi and Salama 2008). He would soon discover, however, that a military built on cultural myths and tribal relations would not work so well against an opponent with an even deeper faith in bravery and martyrdom and a population three times as great.

Politically, the war solidified Khomeini's religious revolution that he set in motion by overthrowing the Shah in 1979. Nevertheless, from the moment the conflict began to its end eight years later, the Iraqis and Iranians consistently overestimated their possibilities as well as underestimated those of their opponents. The war also underlined the extraordinary capacity of human beings, particularly political leaders, to delude themselves that, as the fifth century King Archidamus warned his fellow Spartans, "war is a good thing or a safe thing."

Stripped of its larger context, the conflict may have little to offer in the way of strategic lessons or battlefield accomplishments. Nevertheless, the study of political and military failure, as much as success, develops a deeper understanding of the past, which in turn sheds light on the future and on the nature and character, as well as cultural dispositions, of potential opponents. As the great Greek historian Thucydides suggested, his history, indeed all history, should be "useful [for] those who want to understand clearly the events which happened in the past and which (human nature being what it is) will at some time or other and in much the same ways, be repeated in the future" (Thucydides).

The availability of Iraqi documents and media captured during Operation Iraqi Freedom (OIF) presents a unique opportunity to explore this conflict from within Iraq's decision-making processes. The capture of the Ba'athist state records and their availability for scholarship through efforts like the Conflict Records Research Center has the potential to change how historians, and ultimately the people of the region, understand these events. This study examined Iraq's decision-making processes, but does not provide a detailed historical analysis of the Iran-Iraq War. Where possible, it also aims to present a sense of Iran's actions and perceptions, although without access to the records of the Khomeini regime, this account has less to offer regarding Iran's decision-making.

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"The Iran-Iraq War: A Military and Strategic Show"

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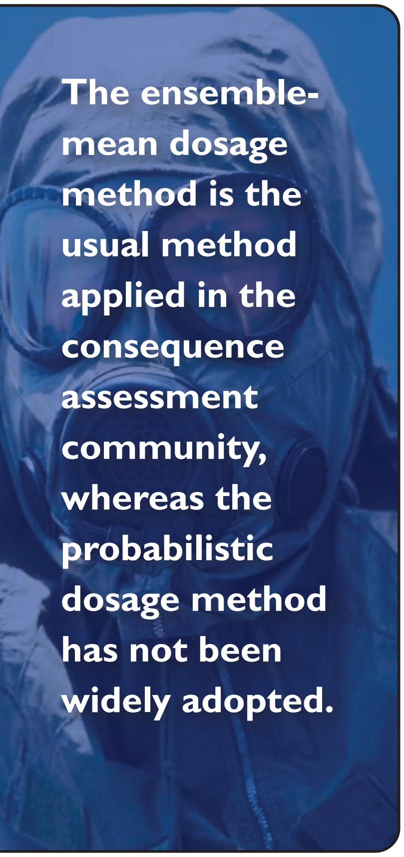
Assessing Atmospheric Releases of Hazardous Materials

Nathan Platt and Jeffry Urban

The Problem

Atmospheric transport and dispersion (AT&D) models play an important role in the Department of Defense because of the threat of battlefield or terrorist use of chemical and biological weapons. There is a need to accurately model the consequences of the intentional or accidental release of hazardous materials into the atmosphere.



The ensemble-mean dosage method is the usual method applied in the consequence assessment community, whereas the probabilistic dosage method has not been widely adopted.

Casualty estimation requires toxicological models that relate chemical exposures to toxic effects on humans. A common assumption is that toxic effects are functions of only the total inhaled dose, which in turn is proportional to the atmospheric dosage (a measure of exposure). When the dosage $D(\mathbf{x})$ at location $\mathbf{x}$ results from a steady exposure, of duration T, to a toxic agent with an atmospheric concentration $C(\mathbf{x})$ (Equation 1), these assumptions are embodied in what is called Haber's law of toxicity.

$$D(\mathbf{x}) = C(\mathbf{x})T \tag{1}$$

While Haber's Law originally was defined for constant concentrations only, the following simple extension of Haber's Law to the case of a dosage $d(\mathbf{x})$ derived from a time-varying concentration $c(\mathbf{x},t)$ (Equation 2) is quite prevalent, although it is not based on empirical data (Sommerville et al., 2006).

$$d(\mathbf{x}) = \int c(\mathbf{x},t)\,dt \tag{2}$$

For any given level of exposure, there is a need to estimate the associated toxic effects. The typical toxicological response model used for consequence assessments of toxic releases is a probit model based on a log-normal distribution described by two parameters: the median effective dosage Eff_{50} and the probit slope b. Equation 3 gives the probability of casualty (or fractional casualties) for a given dosage d:

$$Cas(d) = \Phi\left(b\log_{10}\left(\frac{d}{Eff_{50}}\right)\right) \tag{3}$$

where $\Phi(\bullet)$ denotes the standard normal cumulative distribution function and Eff_{50} is the dosage required to achieve a certain effect (e.g., death, incapacitation) in 50% of the population.

The majority of AT&D models used for consequence assessment predict only a "mean" plume that approximates the ensemble average over a large number of possible turbulent plume realizations. A few AT&D models, in addition to predicting an ensemble-mean dosage or concentration, also include statistical estimates of the variance around the ensemble mean. One example is the Second Order Closure Integrated Puff (SCIPUFF) model (Sykes et al., 2007), which is incorporated in the HPAC modeling system maintained and distributed by the U.S. Defense Threat Reduction Agency (DTRA). The dosage field for a single turbulent realization of the toxic plume, $d(\mathbf{x})$, can be decomposed as

$$d(\mathbf{x}) = \overline{d(\mathbf{x})} + d'(\mathbf{x}) \quad (4)$$

where the overbar denotes the ensemble mean and the prime denotes the turbulent fluctuation about the mean for the single realization. HPAC makes physics-based predictions of the pair $(\overline{d(\mathbf{x})}, \overline{d'^2(\mathbf{x})})$ at each prescribed location $\mathbf{x}$, where $\overline{d(\mathbf{x})}$ is the ensemble-mean dosage and $\overline{d'^2(\mathbf{x})}$ is the variance of dosage fluctuations about the mean value:

$$\sigma^2 = Var[d(\mathbf{x})] = \overline{d^2(\mathbf{x})} - \overline{d(\mathbf{x})}^2 = \overline{d'^2(\mathbf{x})} \quad (5)$$

HPAC also assumes that dosage fluctuations are described by a clip-normal distribution with parameters μ_G and σ_G

$$p_{CN}(d;\mu_G,\sigma_G) = \frac{1}{2}\left(1 - erf\left(\frac{\mu_G}{\sigma_G\sqrt{2}}\right)\right)\delta(d-0) + \frac{1}{\sigma_G\sqrt{2\pi}}\exp\left(-\frac{(d-\mu_G)^2}{2\sigma_G^2}\right), \quad d \geq 0 \quad (6)$$

where erf is the error function and $\delta(d-0)$ denotes the Dirac delta function evaluated at $d = 0$, i.e., $\delta(d-0) = \begin{cases} 1 & \text{if } d = 0 \\ 0 & \text{otherwise} \end{cases}$

The predicted mean and variance of the dosage $(\mu, \sigma^2) = (\bar{d}, \overline{d'^2})$ can be related to the parameters of the clip-normal distribution μ_G and σ_G by the following equations (Sykes et al., 2007):

$$\mu = \frac{\sigma_G}{\sqrt{2\pi}}\exp\left(-\frac{\mu_G^2}{2\sigma_G^2}\right) + \frac{\mu_G}{2}\left(1 + erf\left(\frac{\mu_G}{\sigma_G\sqrt{2}}\right)\right)$$

$$\sigma^2 = -\mu^2 + \frac{\sigma_G^2}{2}\left(1 + erf\left(\frac{\mu_G}{\sigma_G\sqrt{2}}\right)\right) + \mu_G\mu \quad (7)$$

Equation 7 must be numerically inverted to obtain the clip-normal parameters μ_G and σ_G from the HPAC outputs $\bar{d}$ and $\overline{d'^2}$ (μ and σ^2).

Consequence Assessment Using HPAC's Ensemble-Mean Dosage

We now formally introduce an intuitive way of performing consequence assessment based on the ensemble-mean dosage alone. Let $\bar{d}_{\mathbf{x}}$ denote the mean dosage at any given location $\mathbf{x}$. For a prescribed dosage threshold l, define

$$H(d,l) = \begin{cases} 1 & \text{if } d > l \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

The function $H(\bar{d}_{\mathbf{x}}, l)$ therefore indicates whether the mean dosage at a location $\mathbf{x}$ lies above threshold l. Thus, the area over which the mean dosage exceeds the threshold is

$$Area(\bar{\mathbf{d}}, l) = \int_{\mathbf{x}} H(\bar{d}_{\mathbf{x}}, l)d\mathbf{x} \quad (9)$$

Similarly, given a population density $\rho(\mathbf{x})$, the number of casualties is

$$Cas(\bar{\mathbf{d}}) = \int_{\mathbf{x}} Cas(\bar{d}_{\mathbf{x}})\rho(\mathbf{x})d \quad (10)$$

Consequence Assessment Using HPAC's Probabilistic Distribution of Dosages

Next we introduce a methodology to calculate the expected consequences using the probabilistic dosage distribution available in HPAC. For a specified location **x**, assume that individual turbulent realizations of the dosage are distributed according to a clip-normal distribution $p_{CN}(d;\mu_x,\sigma_x)$ given by Equation 6. Then

$$E[H(\bullet,l)] = \int_0^\infty H(\tau,l)p_{CN}(\tau;\mu_x,\sigma_x)d\tau = \int_l^\infty p_{CN}(\tau;\mu_x,\sigma_x)d\tau \quad (11)$$

Here $E[\bullet]$ denotes the statistical expectation with respect to the random variable describing the dosage distribution. We note that, in this formulation, Equation 11 is equivalent to calculating the probability that a randomly distributed dosage at a given location **x** exceeds some threshold value *l*. However, upon applying Equation 6, the right side of Equation 11 is equivalent to the integral of the the density function of the normal distribution from *l* to ∞ (when $l > 0$). For a normal distribution with mean μ_x and standard deviation σ_x, the cumulative density function $\Phi(\bullet;\mu_x,\sigma_x)$ can be computed as:

$$\Phi(d;\mu_x,\sigma_x) = \frac{1}{2}\left[1 + erf\left(\frac{d-\mu_x}{\sigma_x\sqrt{2}}\right)\right] \quad (12)$$

Thus,

$$E[Area(\bullet,l)] = E[H(\bullet,l)] = 1 - \Phi(l;\mu_x,\sigma_x) = \frac{1}{2}\left[1 - erf\left(\frac{l-\mu_x}{\sigma_x\sqrt{2}}\right)\right] \quad (13)$$

This expression gives the probability that the dosage will exceed some threshold value *l* at location **x**. Integrating over all locations x yields the expected (or average) area over which the dosage exceeds *l*:

$$< Area(l) > = \frac{1}{2}\int_{\mathbf{x}}\left[1 - erf\left(\frac{l-\mu_{\mathbf{x}}}{\sigma_{\mathbf{x}}\sqrt{2}}\right)\right]d\mathbf{x} \quad (14)$$

Starting with the expression in Equation 3 for casualties at a single location, the expected number of casualties at a location **x** that has a population density $\rho(\mathrm{x})$ can be calculated via numerical integration of

$$E[Cas(\bullet)] = \int_0^\infty Cas(\tau)p_{CN}(\tau;\mu_{\mathbf{x}},\sigma_{\mathbf{x}})\rho(\mathbf{x})d\tau \quad (15)$$

The expected casualties from the hazardous plume are:

$$< Cas > = \int_{\mathbf{x}}\int_0^\infty Cas(\tau)p_{CN}(\tau;\mu_{\mathbf{x}},\sigma_{\mathbf{x}})\rho(\mathbf{x})d\tau d\mathbf{x} \quad (16)$$

Brief Description of a Small-Scale Chemical Attack

In order to compare these consequence estimation methodologies, we simulated a notional small-scale chemical artillery attack of 18 individual artillery rounds impacting simultaneously within a 200-meter by 100-meter target box (Figure 1), with each round dispersing 1.6 kg of chemical agent. We created six sets of HPAC predictions using wind speeds of 5, 10, and 15 km/hr with the Pasquill-Gifford atmospheric stability categories of moderately stable (PG3) and slightly unstable (PG6), roughly corresponding to certain nighttime and daytime release conditions, respectively. We calculated hazard areas and numbers of casualties using the previously described methodologies. We also examined the "on target" hazard areas and casualties occurring only within the 200-meter-by-100-meter attack box. To better understand the effects

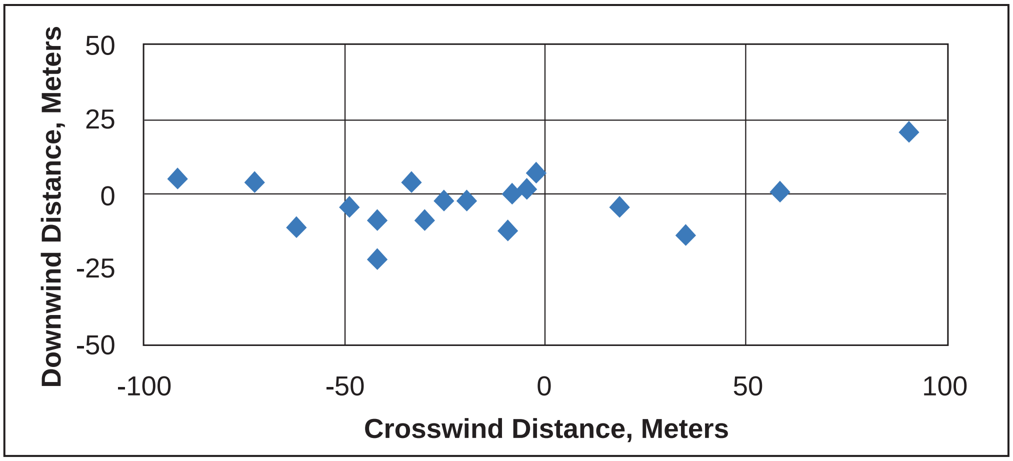


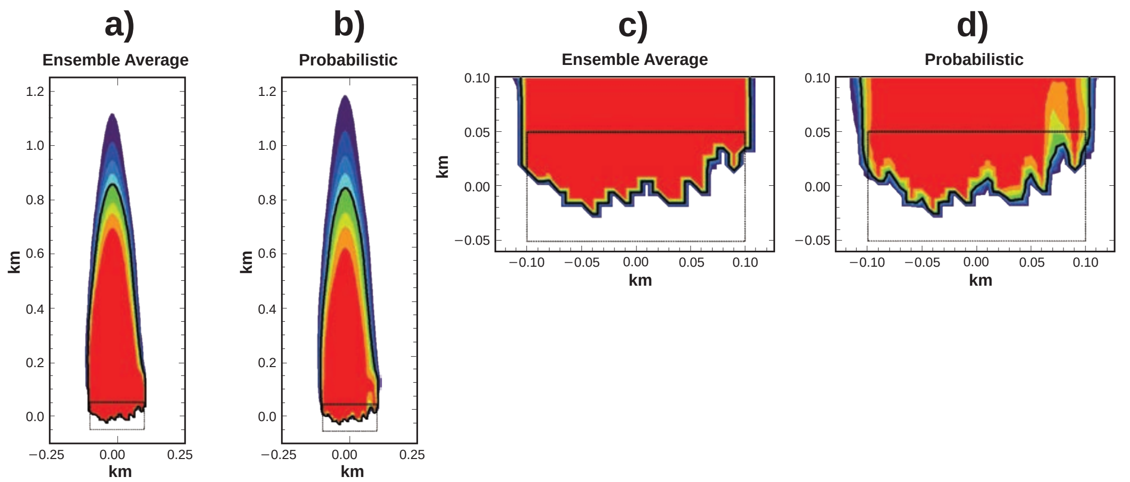
Figure 1. Relative Locations of 18 Individual Chemical Source Terms

of dosage threshold on hazard area calculations, we considered notional hazards occurring at seven different likelihoods of lethality: LCt_{99}, LCt_{90}, LCt_{50}, LCt_{5}, LCt_{1}, and $LCt_{0.1}$, where LCt_{x} ("lethal concentration *x*") is the concentration at which *x*% of the exposed population would die without medical intervention. The principal metric we used is the ratio of the expected hazard area or number of casualties estimated probabilistically from Equation 14 or 16 to the expected hazard area or number of casualties estimated from the ensemble-mean dosage plume using Equation 9 or 10.

Brief Summary of the Results

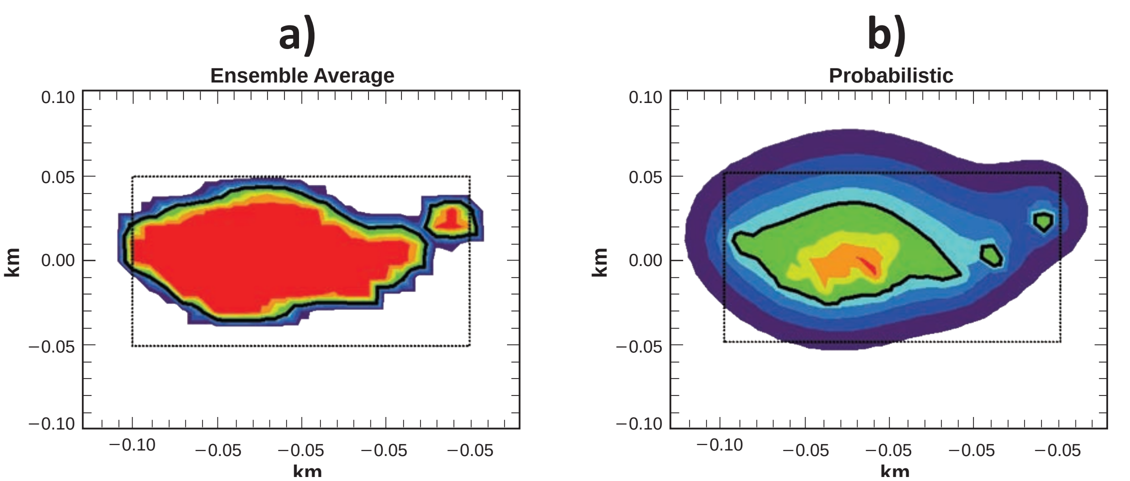
Figures 2 and 3 depict typical fractional lethality contours in the case of a moderately stable (PG6) or slightly unstable (PG3) atmosphere. Fractional casualties is the fraction of the exposed population that is expected to suffer casualties at the specified toxic endpoint (e.g., death). The thick black contour corresponds to a fractional lethality of 0.5, and the black dotted rectangle denotes the on-target attack box. In the case of moderately stable atmospheric conditions, the differences between the casualty contours generated using the two different methods are minor, especially when one considers the full extent of the contours (Figures 2a and 2b) instead of only the on-target attack box (Figures 2c and 2d). However, in the case of slightly unstable atmospheric conditions, the differences between the two methods of estimating casualties are significant (Figures 3a and 3b). These differences include both the locations at which casualties are expected to occur (larger areas for using the probabilistic dosage method than the ensemble-mean dosage method) and the number of casualties at individual locations (significantly larger at most locations using the ensemble-mean dosage method).

Figure 4 depicts the ratios of expected casualties based on probabilistic dosages to casualties based on ensemble-averaged dosages for the two atmospheric stability categories and three wind speeds considered in this analysis. For moderately stable atmospheric



Panel a) depicts contours calculated from the ensemble-averaged dosage, panel b) depicts contours calculated from a clip-normal probabilistic dosage distribution, and panels c) and d) zoom in on the on-target attack box depicted in panels a) and b).

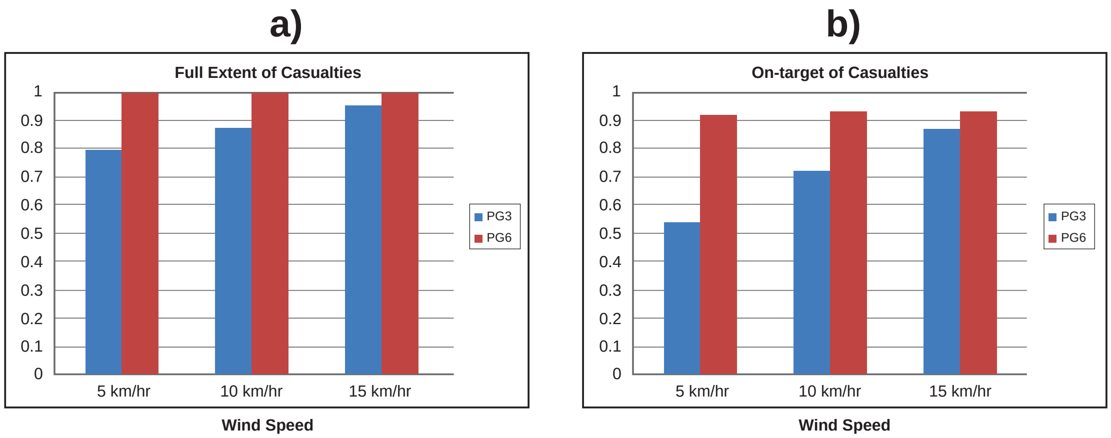
Figure 2. Fractional Lethality Contours for a Moderately Stable Atmosphere (PG6) and a Wind Speed of 10 km/hr



Panel a) depicts contours calculated from the ensemble-averaged dosage, and panel b) depicts contours calculated from a clip-normal probabilistic dosage distribution.

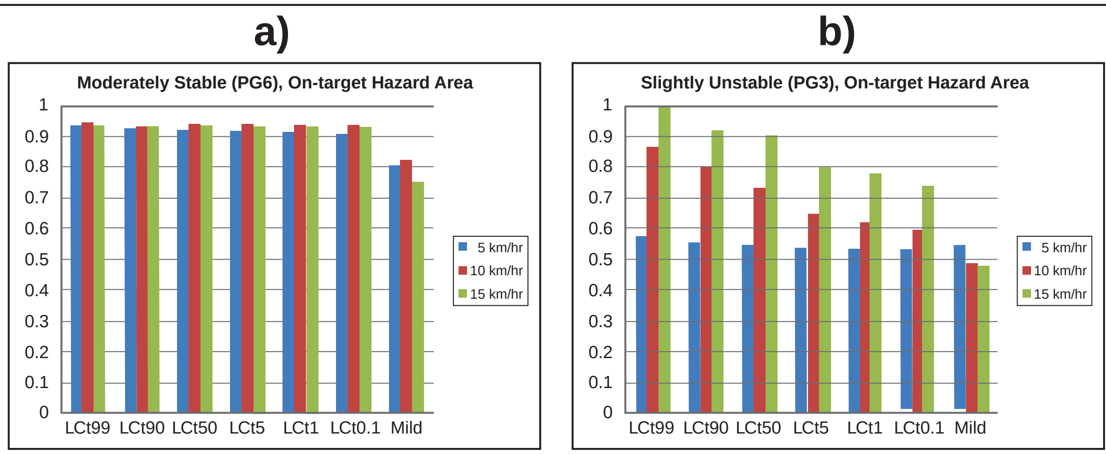
Figure 3. Fractional Lethality Contours for a Slightly Unstable Atmosphere (PG3) and a Wind Speed of 10 km/hr

conditions, the casualty ratio is close to 1, indicating that both methods of estimating casualties produce similar results. However, when the atmospheric conditions are slightly unstable, varying wind speed yields casualty ratio variation from 0.55 to 0.94, indicating that the ensemble-mean dosage method of calculating casualties can result in significantly higher casualty estimates than the probabilistic dosage method.



In panel a), casualties are calculated over full extent of the plume, and panel b) casualties are calculated only within the on-target attack box.

Figure 4. Ratio of Expected Lethalities



Panel a) correspond to moderately stable atmospheric conditions (PG6) and panel b) correspond to slightly unstable atmospheric conditions (PG3).

Figure 5. Ratios of the Expected Hazard Areas

Figure 5 depicts the ratios of the hazard area calculated based on probabilistic dosages to the hazard area calculated based on the ensemble-mean dosage for two atmospheric stability categories, three wind speeds, and seven notional toxic effects levels for on-target attacks. For moderately stable atmospheric conditions, the two methods of consequence assessment yield similar values (Figure 5a). In the case of a slightly unstable atmosphere (Figure 5b), there is a greater spread in the hazard area ratios that depends on the level of effects and the wind speed with potential difference up to a factor of two in the size of the predicted hazard area.

Conclusions

We simulated a small-scale chemical weapons attack to investigate the implications of using two methods for dosage-based consequence assessment: one using the HPAC model's probabilistic predictions of agent dosage, and one using HPAC's ensemble-mean predictions of dosage. We note that the ensemble-mean dosage method is the usual method applied in the consequence assessment community, whereas the probabilistic dosage method has not been widely adopted.

Our main conclusion is that care should be exercised when using an ensemble-mean dosage plume to calculate the consequences from an atmospheric release of toxic materials. We found that at least for our single small-scale chemical attack scenario considered under a few different meteorological conditions, the two methods of dosage-based consequence assessment yielded similar results in the case of moderately stable atmospheric conditions, but dissimilar results in the case of slightly unstable atmospheric conditions. In the latter case, depending on wind speed and the size of the targeted area, an over-prediction of consequences of up to a factor of two is possible when using the commonplace ensemble-mean dosage method. Additionally, the spatial distribution of casualties and hazard areas could differ significantly between these two methods of performing consequence assessment.

We note a significant conceptual difference between these two approaches to dosage-based consequence assessment. AT&D models that predict ensemble-mean dosages have the advantage of being able to produce a plot of the "average" plume. Since the toxicity equations that map dosages to adverse health effects are nonlinear, consequence estimates based on these ensemble-averaged plumes do not represent ensemble-averaged casualties or hazard areas. On the other hand, AT&D models that are capable of producing probabilistic dosage distributions can be used to calculate average casualties or hazard areas correctly, but the probabilistic description does not readily lend itself to producing easy-to-interpret plots of the location of the hazard. Moreover, it might be possible to calculate uncertainties associated with the consequences of the attack such as variance of the casualty estimate.

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http://inderscience.metapress.com/content/mv272xnjh59ml572/

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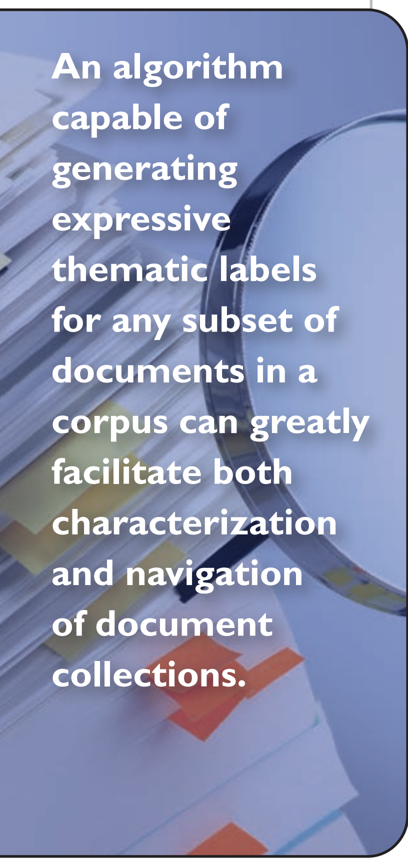
Visual Analytics for Large Document Sets

Arun S. Maiya and Robert M. Rolfe

The Problem

We examine what we refer to as topic similarity networks: graphs in which nodes represent latent topics in text collections and links represent similarity among topics. Efficient and effective approaches to both building and labeling such networks are described. Visualizations of topic models based on these networks are shown to be a powerful means of exploring, characterizing, and summarizing large collections of unstructured text documents



In our article, we examine network visualizations as a means of enhancing the interpretability of probabilistic topic models for insight discovery. We focus on what is perhaps the most popular and prevalently used topic model: latent Dirichlet allocation or LDA (Blei, Ng and Jordan 2003). Topic modeling algorithms like LDA discover latent themes (i.e., topics) in document collections and represent documents as a combination of these themes. Thus, they are critical tools for exploring text data across many domains. It is often the case that users must discover the subject matter buried within large and unfamiliar document sets (e.g., sensemaking in text data). Keyword searches are inadequate here, since even to begin searching is unclear. Topic discovery techniques such as LDA are a boon to users in such scenarios, because they reveal the content in an unsupervised and automated fashion. However, obtaining a "big picture" view of the larger trends in a document collection from only the raw output of an LDA model can be challenging. In our article, we investigate, the use of what we refer to as topic similarity networks to address this challenge. Topic similarity networks are graphs in which nodes represent latent topics in text collections, and links represent similarity among topics. We described efficient and effective methods to both building and labeling such networks.

Preliminaries

Let $D=\{d_1,d_2,....,d_N\}$ represent a document collection of interest and let K be the number of topics or themes in D. Each document is composed of a sequence of words: $d_i=\langle w_{i1},w_{i2},\ldots,w_{iN_i}\rangle$ where N_i is the number of words in d_i and $i\in\{1\ldots N\}$. Let $W={}_{i=1}^{N}f(d_i)$ be the vocabulary of D, where $f(\cdot)$ takes a sequence of elements and returns a set. Probabilistic topic models like LDA take D and K as input and produce two matrices as output. The matrix $\theta\in R^{N\times K}$ is the document-topic distribution matrix, which shows the distribution of topics within each document. The matrix $\beta \in R^{K \times |W|}$ is the topic-word distribution matrix, which shows the distribution of words in each topic. Each row of these matrices represents a probability distribution. For any topic $i \in \{1,\ldots,K\}$, the L terms with the highest probability in distribution β_i are typically used as thematic labels for the topic. We use these LDA-derived labels as a baseline for comparison in our work. We begin by describing the construction of the topic similarity network.

Constructing the Network

LDA captures the degree to which both documents and words are topically related. However, relations among the topics themselves are not explicitly captured. In this section, we define these relations by measuring topic similarity.

Measuring Topic Similarity

Recall that topics are represented as probability distributions over vocabulary W and captured by the matrix β. Thus, the similarity for any two topics can be directly computed by comparing the word distributions from β. We employ the Hellinger distance metric to compute topic similarity. Specifically, for any two topics $x,y \in \{1\ldots K\}$, the Hellinger similarity is measured as:

$$H_S(\beta_x,\beta_y)=1-\frac{1}{\sqrt{2}}\sqrt{\sum_{i=1}^{|W|}(\sqrt{\beta_{xi}}-\sqrt{\beta_{yi}})^2}. \quad (1)$$

A topic similarity network $G=(V,E)$ can be constructed where $V=\{v_1\ldots v_K\}$ is the set of nodes representing discovered topics and E is the set of edges representing similarities among topics. For any two topics $x,y \in \{1\ldots K\}$, an edge $\{v_x,v_y\} \in V$ exists if and only if $H_S(\beta_x,\beta_y)$ is greater than some predefined threshold, ξ. A MapReduce implementation of these computations is also possible.

Discovering Larger Themes

We employ the use of a community detection algorithm to discover insights into how topics are related to each other and form larger themes. A *community* can be loosely defined as a set of nodes more densely connected among themselves than to other nodes in the network (Blondel, et al. 2008). Within the context of a topic similarity network, such communities should represent groups of highly related topics, which we refer to as topic groups. To detect these communities (or topic groups), we employ the use of the Louvain algorithm, a heuristic method based on modularity optimization (Blondel, et al. 2008).

Labeling the Network

An algorithm capable of generating expressive thematic labels for any subset of documents in a corpus can greatly facilitate both characterization and navigation of document collections. Here, we employ such an algorithm to label nodes in a topic similarity network, as each node is a topic comprising a subset of documents in the corpus. Our approach, referred to as DOCSETLABELER, is a purely unsupervised, extractive method and shown in Algorithm 1. DOCSETLABELER takes D_S, a subset of corpus D, as input, where D_S consists

Algorithm 1 DocSetLabeler algorithm

Require: $D_S \subset D$, a subset of corpus D
Require: C, the number of candidate terms to consider
Require: L, the number of labels to return for document set ($L \leq C$)
Require: stopwords, list of terms to filter out
pos = a hash table
neg = a hash table
for all $d \in D$ **do**
  terms1 = extractSignificantPhrases(*d,* stopwords)
  terms2 = extractNounPhrases(*d,* stopwords)
  terms3 = extractProperNounUnigrams(*d,* stopwords)
  candidates = (*terms1* ∩ *terms2*) ∪ *terms3*
  for all $c \in candidates$ **do**
    x = normalized frequency of term c in d
    $y = 1 - \frac{\text{index of first occurrence of c in } d}{\text{num. of words in d}}$
    $(\text{weight of term } c) = \frac{2 \cdot x \cdot y}{x + y}$
  end for
  If $d \in D_S$ **then**
    pos[d] = top C terms based on weight
  else
    neg[d] = top C terms based on weight
  end if
end for
for all $\ell \in \bigcup_{x \in pos.values()} X$
  # compute information gain for each label ℓ
  (score of label ℓ) = calcScore(ℓ, pos, neg)
end for
top_candidates= top C labels based on information gain
optionally re-sort final top candidates
top candidates = re_sort(*top_candidates*)
return top L labels from *top_candidates*

of all documents associated with some LDA-discovered topic $t \in \{1 \ldots K\}$. In the present work, D_S is constructed by transforming topics into mutually exclusive clusters, where the topic cluster for document d_i is $\text{argmax}_x \theta_{ix}$ (for $i \in \{1 \ldots N\}$). Each cluster is an input D_S to Algorithm 1.

DOCSETLABELER is essentially a descriptive model of topic labeling that follows naturally from four observed characteristics of high-quality, topic-representative labels: Expressivity, Prominence, Prevalence, and Discriminability.

Expressivity

Expressivity captures the extent to which labels express and represent themes. Human-assigned labels tend toward multi-word noun phrases, as they are more expressive than unigrams. Unigrams tend to be most expressive when denoting uniqueness (i.e., a proper noun). This is especially true of research reports, our domain of interest, as proper noun unigrams denote important concepts, systems, techniques, or programs (e.g., "LinearSVM," "F-22"). Lines 4-6 in Algorithm 1 explicitly extract terms conforming to the above principles. The extractSignificantPhrases(•) function uses likelihood ratio tests to extract phrases of multiple words that occur together more often than chance. For a bigram of words w_1 and w_2, this association, *assoc*(·,·), is measured as:

$$assoc(w_1,w_2)=2\sum_{ij} n_{ij}\log\frac{n_{ij}}{m_{ij}}, \qquad (2)$$

where n_{ij} are the observed frequencies of the bigram from the contingency table for w_1 and w_2 and m_{ij} are the expected frequencies assuming that the bigram is independent.

Prominence

Prominence captures the degree to which labels are featured prominently within individual documents. Intuitively, prominent terms tend to make their first appearance earlier and also appear more frequently. Thus, we weight candidate labels by both frequency and position using the harmonic mean, as shown in Line 11 of Algorithm 1.

Prevalence and Discriminability

Good labels for a particular topic appear in many documents pertaining to that topic (*Prevalence*) and appear rarely in other unrelated topics (*Discriminability*). The concept of information gain from the field of information theory simultaneously captures both prevalence and discriminability. Consider a document collection D where documents belong to either a positive or negative category. The *entropy* H of D measures impurity as follows: $H(D)=-p^{+}\log_2(p^{+})-p^{-}\log_2(p^{-})$, where $p+$ and p- are the proportions of positive and negative documents in D, respectively.[1] In Algorithm 1, we assign D_S as positive and $\overline{D_S}$ as negative. The information gain IG of a candidate label ℓ in D, then, is the expected entropy reduction due to segmenting on ℓ:

$$IG(\ell,D)=H(D)-\left(\frac{|D^{\ell}|}{|D|}H(D^{\ell})+\frac{|\overline{D^{\ell}}|}{|D|}H(\overline{D^{\ell}})\right),$$

where D^{ℓ} is the set of documents in D from which label ℓ was extracted. Information gain is computed by the *calcScore*(•) function in Algorithm 1. At the end of the previous step, we are left with a small number of candidate labels (e.g., C=5) for each topic. One can simply select the label with the highest information gain (i.e., the existing sorting) or re-sort based on a combination of other factors (e.g., label frequency, word probabilities from β), as indicated in Line 25 of Algorithm 1.

[1] Note that log²(0) is taken to be 0.

Case Study: NSF Research Grants

As a realistic and informative case study, we utilize our methods to characterize and visualize basic research funded by the National Science Foundation (NSF). The corpus considered in this case study consists of 132,372 titles and abstracts describing NSF awards for basic research between the years 1989 and 2003 (Bache and Lichman 2013). We executed the MALLET implementation of LDA (McCallum 2002) on this corpus using K=400 as the number of topics and 200 as the number of iterations. All other parameters were left as defaults. For topic similarity, we experimentally set ξ as 0.15 to yield a graph density of approximately 0.01. For the labeling of topic nodes in the network using DOCSETLABELER, we set C=5 and L=1.

Topic Labeling of NSF Grants

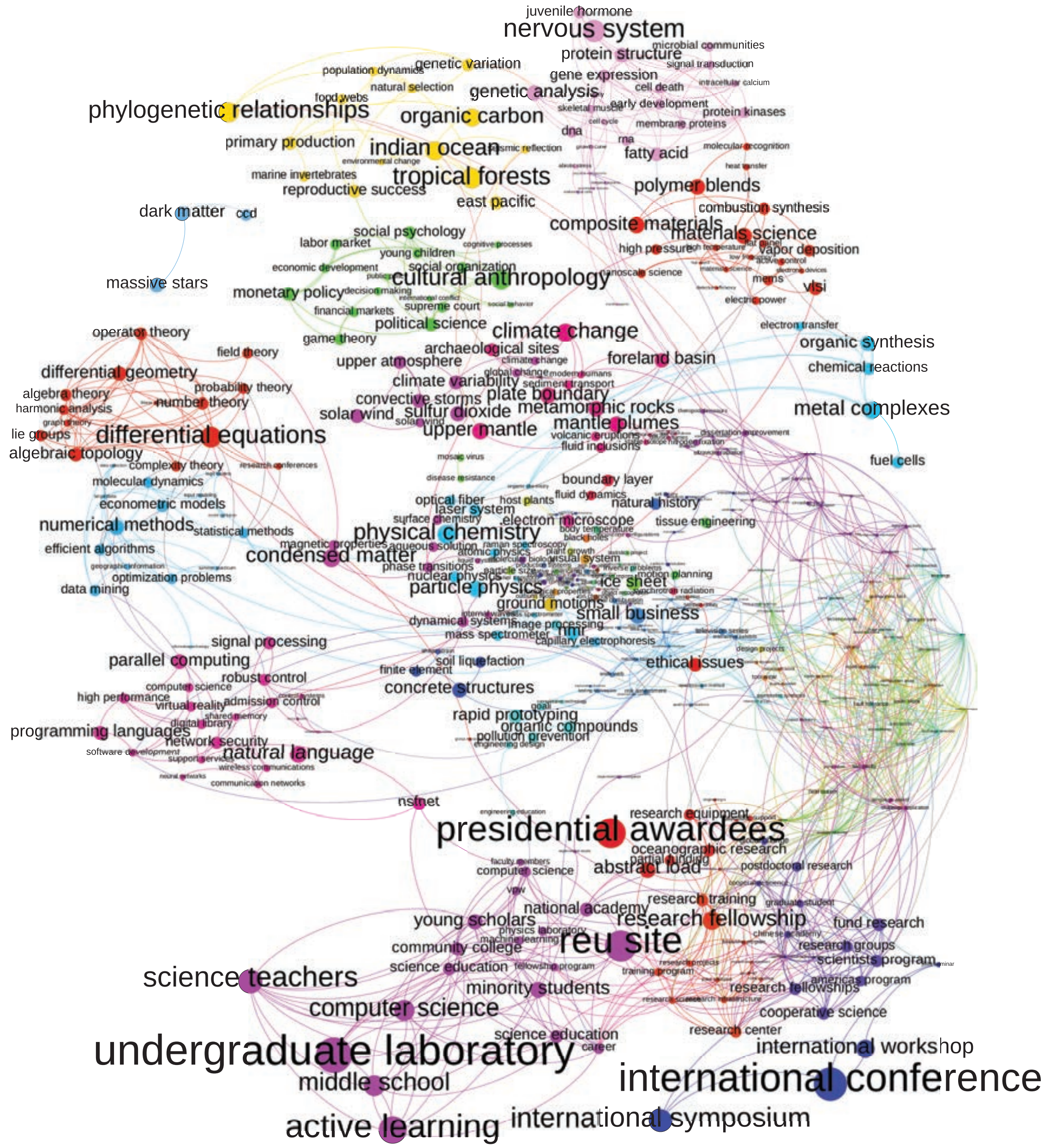
Table 1 shows the labels generated for a sample of ten discovered topics by both DOCSETLABELER and LDA. Labels produced by DOCSETLABELER are more expressive and representative of the true themes of each topic. We assigned two judges to evaluate labels for all topics. For a fair comparison, we showed six unigram labels from LDA but only three labels (mostly bigrams) from DOCSETLABELER for each topic. As shown in Table 2, both judged the labels by DOCSETLABELER to be generally superior (χ^2=145.73, P<0.0001) with an inter-judge agreement of 0.62, as measured by Cohen's kappa coefficient.

Visualizing NSF Grants

A topic similarity network was constructed, with each node representing a topic and labeled using the highest ranked term returned by DOCSETLABELER. The network, which concisely presents a comprehensive and holistic view of roughly 15 years of NSF-funded research, can be navigated and explored using any available network visualization software (e.g., Gephi, Cytoscape). The entire network is shown in Figure 1, where both expected and unexpected trends are revealed. The visualization encapsulates the major research funding efforts for scientific research in addition to the subtle connections among them. Major funding efforts for education and conference support are also displayed (toward the bottom). In this network and all networks shown in our article, node sizes indicate the number of documents pertaining to the topic represented by the node. Sizing nodes by funding amount is also possible. Node colors indicate the community (or topic group) affiliation. Using this network, one can better understand how topics form larger themes, discover and characterize information of interest, and derive insights into how best to search and explore the corpus further. We present illustrative examples of the patterns and trends discovered using our topic similarity network. Figure 2 shows one small corner of the "topic universe" — a "social clique" of math topics discovered by community detection within the larger network of all topics. Note that each node in the network represents hundreds of documents (or more). Thus, this visualization of math topics clearly

Table 1. [NSF Grants.] Ten discovered NSF topics and the highest-ranked labels assigned to each by both LDA and DocSetLabeler.

Actual Topic	Labels from LDA	Labels from DocSetLabeler
Fluid Mechanics and Fluid Dynamics	Flow, fluid, flows, fluids, dynamics, transports	Fluid dynamics, fluid mechanics, multiphase flow
Game Theory	Agents, theory, game, agent, games, equilibrium	Game theory, economic agents, repeated games
Graph Theory	Discrete, graph, combinatorial, theory, combinations, graphs	Graph theory, algebraic combinatorics, ramsey theory
Human Evolution	Modern, fossil, early, years, human, age	Modern humans, human evolution, hominid evolution
Hydrology	Water, river, hydrologic, watershed, balance, surface	Hydrologic controls, watershed scale, alpine basins
Modal Analysis in Structural Engineering	Mode, modes, research, vibration, direction, coupling	Normal modes, vibration control, modal analysis
Object Recognition	object, objects, features, recognition, oriented, feature	Object recognition, curved objects, cluttered scenes
Protein Function/Mechanisms	Protein, proteins, function, role, biochemical, phosphorylation	Protein kinases, protein phosphorylation, protein import
Protein Struction	Protein, proteins, binding, structure, amino, acid	Protein structure, protein folding, amino acid
Social Psychology	Social, people, research, individuals, attitudes, status	Social psychology, social influence, social perception



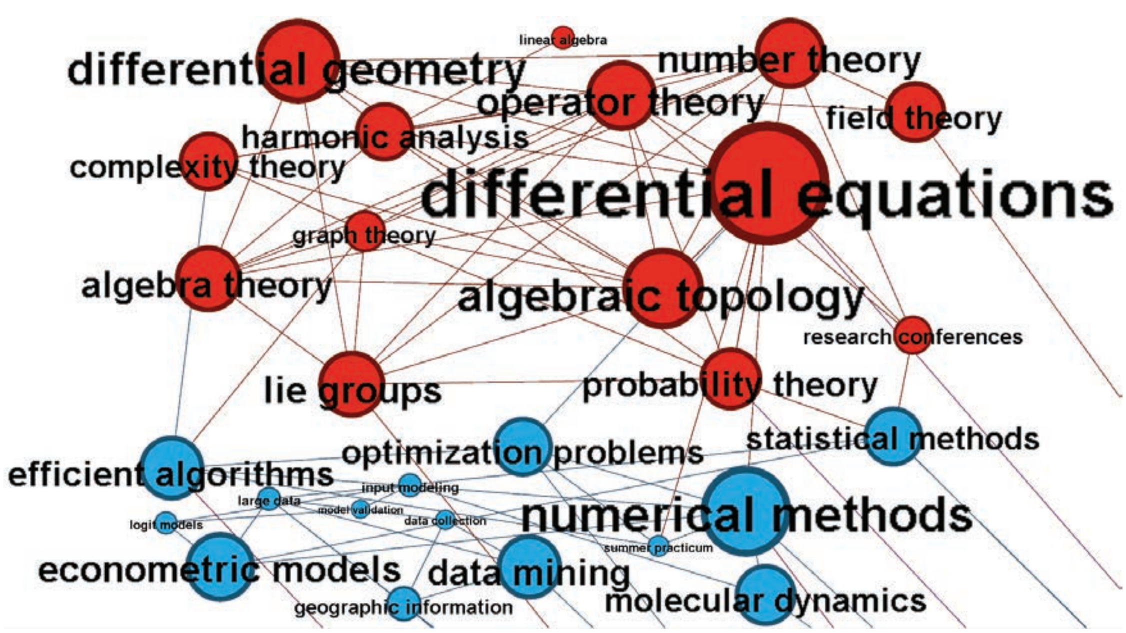
Major research topics – including their subtle connections to each other – are shown. Also displayed (toward the bottom of network) are major funding efforts for education support and conference support. Node sizes indicate the number of grant abstracts pertaining to the topic. Node colors indicate the community (or topic group) affiliation, which illustrate how research topics form larger themes.

Figure 1. [NSF Grants] Topic Similarity Network of Roughly 15 years of NSF research and support (i.e., a Total of 132,372 Research Grants)

Table 2. Evaluation of Labels for Each Method on NSF Grants

	DocSetLabeler	LDA
DocSetLabeler	313	6
LDA	23	29

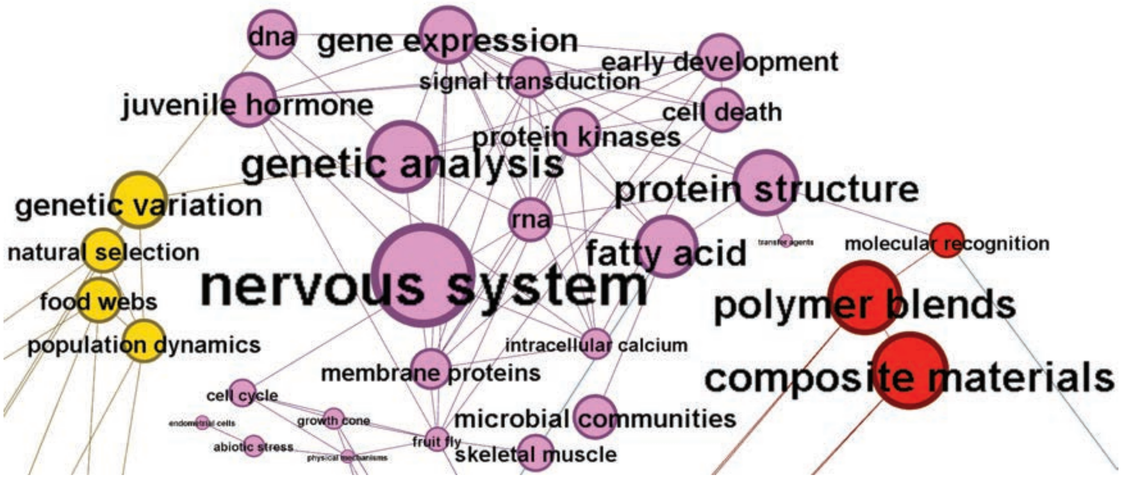
Overall, both judges chose labels from DOCSETLABELERbe most on-point.



The red color covers pure math, while the blue is more applied.

Figure 2. [NSF Grants] Two Discovered Topic Groups (or Communities) Pertaining to Math-Oriented Research

and concisely summarizes more than 10,000 documents. Such visualizations also provide insights into relations between topic groups. For instance, Figure 3 shows a community of biology-related topics (shown in pink). Here, we see peripheral connections to another life science theme (shown in yellow) containing topics such as *genetic variation, population dynamics*, and *food webs*. We also see a peripheral connection to a material science theme (shown in red), illuminating research areas dedicated to developing materials based on biological and organic components and also the mutual interest in molecular recognition. As a final example, Figure 4 shows a connected component of astronomical research topics that appears separate from the larger network. This last example



The topic group related to biology is shown in pink. Also shown are topic nodes from other related communities (e.g., polymer blends, population dynamics) and their peripheral connections to this biology-related topic group.

Figure 3. [NSF Grants] A Discovered Topic Group Related to Biology (shown in pink)

Figure 4. [NSF Grants.] Connected Component of Astronomical Research Topics Separated from the Larger Network

illustrates one possible way to use these visualizations to identify outliers (i.e., topics that are comparatively more different than the larger corpus based on their set of similarity scores).

For additional results and technical details for this analysis, refer to the full report (Maiya and Rolfe October 2014).

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"Topic Similarity Networks: Visual Analytics for Large Document Sets"

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National Science Foundation's Role in Additive Manufacturing

Vanessa Peña, Bhavya Lal, and Maxwell Micali

The Problem

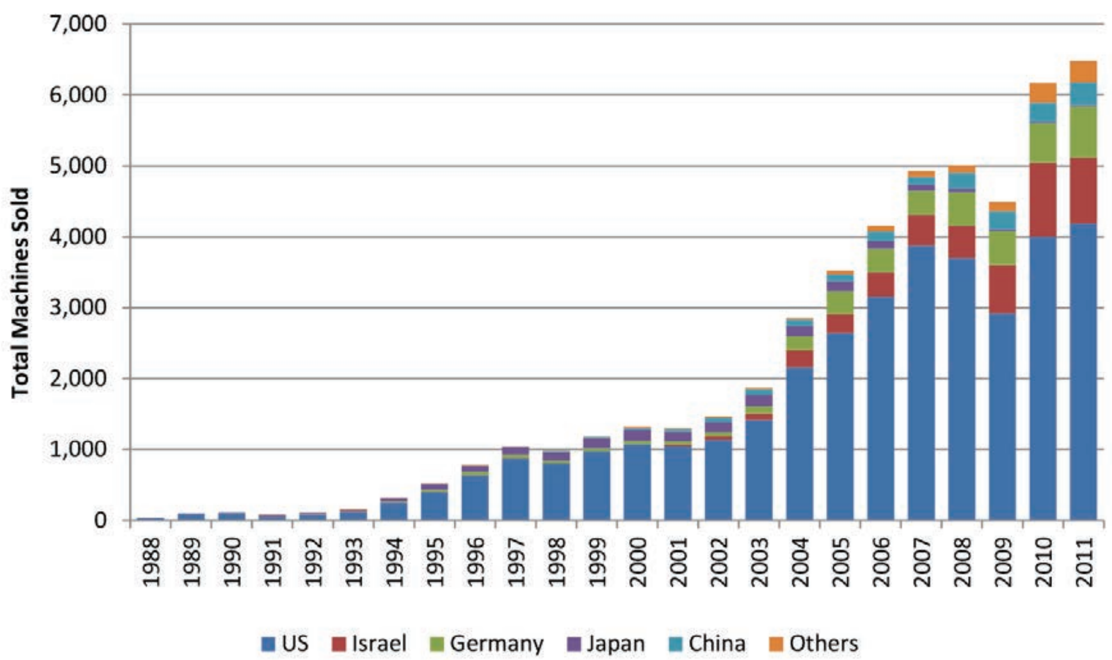
To help the government promote emerging science and engineering at government institutions, the authors investigated lessons learned from the evolution of the additive manufacturing field and the role of U.S.-based funders (particularly the National Science Foundation) in its development and commercialization.

Government agencies should support the broader R&D ecosystem by facilitating expertise among students, encouraging start-ups, contributing to prioritization and planning, and helping create a community in the emerging additive manufacturing field.

Our analysis revealed that government funding to both academic and industrial researchers was instrumental in the origin and evolution of the field, with industry often leading the frontier. Three key lessons emerged for federal research and development (R&D) funding agencies: (1) provide consistent funding over long timespans, (2) support R&D and the transition of research from invention to proof-of-concept, and (3) bolster the ecosystem surrounding R&D.

Additive manufacturing (AM), also referred to as solid freeform fabrication or 3D printing, is a set of layer-by-layer processes for producing three-dimensional objects directly from a digital model. As of 2012, the AM industry had grown in the 20 years since its inception to a nearly $3 billion industry and is poised to reach an estimated $6.5 billion by 2019 (Wohlers 2012). The United States has been home to many successful AM companies, including 3D Systems, Stratasys, Z Corporation, and Solidscape. Figure 1 shows distribution of machine sales from 1988 through 2011. More than 70 percent of the professional-grade, industrial machines sold since the technology's infancy have been sold by U.S. companies; more than 60 percent of the total were sold by Stratasys, Z Corporation, and 3D Systems (Wohlers 2012). Other countries have been players as well, with European countries leading in development of metals and laser-based AM processes.

The history of AM technology points to the roles of various institutions—public funders, private entrepreneurs and inventors, universities, and others—in its development. We found that although researchers had captured portions of the history of AM through journal publications, books, and other resources, few had attempted to explicitly connect events and inventors to public support. Such a mapping reveals lessons learned for creating new fields and promoting innovation. The findings are derived from an examination by the authors and their STPI colleagues published in the IDA Paper titled *The Role*



Source: Data from Wohlers (2012).

Figure 1. Total Machine Sales by Company Aggregated to Country of Ownership

of the National Science Foundation in the Origin and Evolution of Additive Manufacturing in the United States. That 2012 report focused on the NSF's role in the technology's development. This article summarizes the findings and lessons learned with the goal of identifying, nurturing, and promoting emerging science and engineering at government institutions that have mandates related to advancing public good.

Terminology

Standard terminology outlined in 2012 by ASTM International, an international standards-setting body, is used when referring to AM processes, except when the inventors' original process names provide clarity or historical context (ASTM F2792-12a 2012). The seven AM processes include binder jetting, directed energy deposition, material extrusion, material jetting, powder-bed fusion, sheet lamination, and vat photopolymerization.

Methods

Information was gathered from a literature review, structured discussions with experts, analysis of the AM patent landscape and history, and analysis of various types of NSF program awards (Table 1) to identify the most important advances in the field and trace them to the institutions involved in developing them.

The paper examined six case studies and the role of the NSF in specific AM developments (Table 2). We identified the top 100 patents and four foundational patents based on

Table 1. Methods, Data Sources, and Description of Purpose

	Method	Data Sources	Purposes
Qualitative	Literature review	>100 peer-reviewed journals; textbooks; conference proceedings; workshop, task force, and industry reports; and patents	• Understand origins and development of AM • Search for references to historically important patents
	Structured interviews	25 AM experts: • 8 U.S. academic • 5 industry • 9 federal government, including 3 NSF program managers • 3 non-U.S. researchers	• Understand opinions on historically important events, technologies (patents), people, institutions, and networks • Identify opinions of NSF's role in AM
	Case studies	Cases on 6 technologies/patents: • 4 foundational patents (citations from literature, patents, and interviews) • 2 patents with known NSF impact	• Understand the development of specific AM processes, in depth • Identify NSF influence through patent analysis (including cited/citing patents)
Quantitative	AM patents	3,822 U.S. patents from 1975 to 2011 (identified Rapid Prototyping Patent Database[a] and metadata—assignees, cited patents, etc.—from U.S. Patent and Trademark Office)	• Analyze trends and growth in AM technologies through patenting activity • Identify highly influential technologies (highly cited through patent citations)
	NSF awards	593 awards from 1986 to 2012 (identified through 165 culled keywords)	• Analyze trends in number of awards, funding, NSF directorates, and topics

[a] Rapid Prototyping U.S. Patent Database available online.

AM, additive manufacturing; NSF, National Science Foundation.

Table 2. Four Foundational and Two NSF-Impacted AM Patents and Processes

	AM Process	U.S. Patent Number and Title	Inventor(s)	Application Year
Foundational	Vat photopolymerization	4575330: Apparatus for production of three-dimensional objects by stereolithography	Charles Hull	1984
	Powder bed fusion	4863538: Method and apparatus for producing parts by selective sintering	Carl Deckard	1986
	Material extrusion	5121329: Apparatus and method for creating three-dimensional objects	S. Scott Crump	1989
	Binder jetting	5204055: Three-dimensional printing techniques	Emanuel Sachs John Haggerty Michael Cima Paul Williams	1989
NSF-Impacted	Sheet lamination	4752352: Apparatus and method for forming an integral object from laminations	Michael Feygin	1987
	Contour crafting	5529471: Additive fabrication apparatus and method	Behrokh Khoshnevi	1995

expert feedback, patent citations, and a literature citation analysis from 29 review articles of the AM field. We analyzed two additional patents with known NSF influence in the AM field to further explore the role of NSF's support for research and technology developments.

Since AM is an application-oriented field, patent analysis, which is related more to technology breakthroughs than scientific and technical publications, was favored over bibliometric analysis as the primary analytic tool. We analyzed almost 4,000 patents extracted from existing databases, supplemented with U.S. Patent and Trademark Office metadata, including inventors, assignee organization, government interest, file and issue dates, and references both cited by the patent ("backward citations") and citing the patent ("forward citations"). In addition, we culled and analyzed almost 600 NSF awards relevant to AM that provided us with insight into NSF's historical support of AM.

Results

The analysis provided insight into industry's role in developing the AM field, the origins and evolution of leading technologies, the role of the government in specific seminal inventions, and the role of NSF in supporting AM research, technology development, networking, and coordination activities.

Industry Dominates Patent Development

The overall finding was that innovation in AM has been dominated by the private sector, especially when it comes to the total number of patents and the continual advancement of the technology beyond initial invention (Figure 2). More than 90 percent of the AM patents were held by firms during the 35-year period examined.

Trends in the Origins and Evolution of Leading Technologies

In analyzing the selected top 100 AM patents, we observed an initial phase of modern discoveries, which increased rapidly in the late 1980s. This period included the inventions from Charles Hull and the formation of 3D Systems, a current industry leader, as the company began to expand its patent portfolio. Carl Deckard from the University of Texas and later Scott Crump and Emanuel Sachs from the Massachusetts Institute of Technology (MIT) patented their seminal technologies around this same time. The late 1990s and onward was a period of continued process improvements, technology

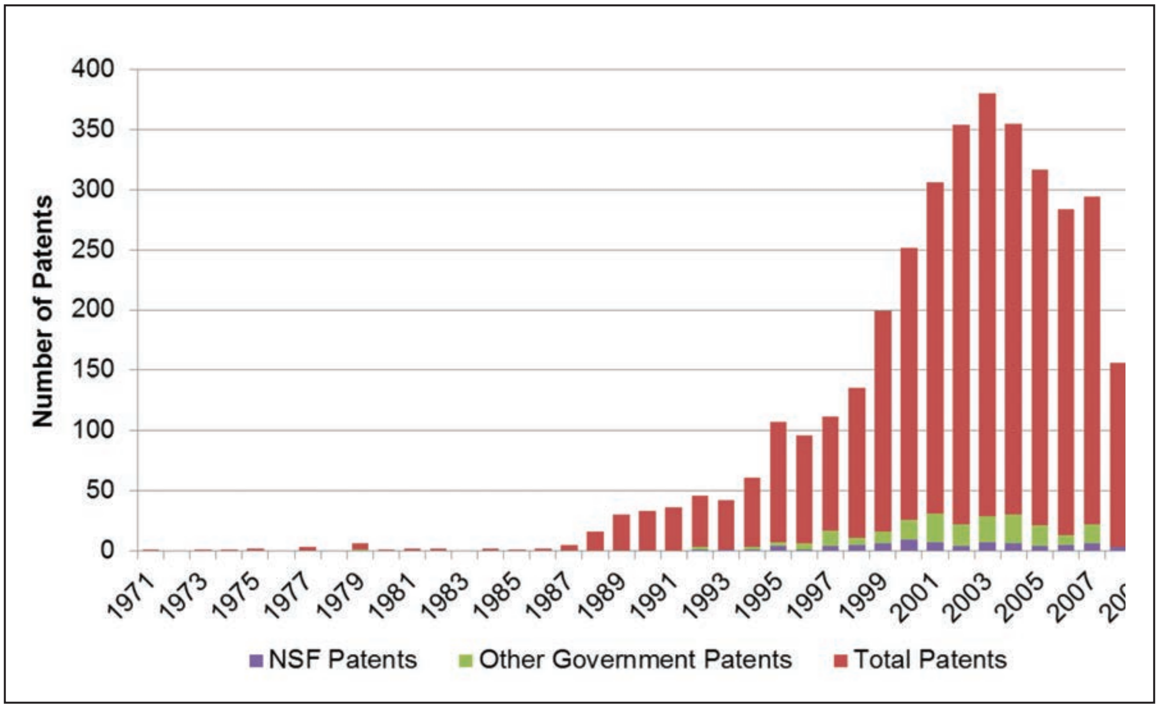


Figure 2. Industry Dominates U.S. Patents in AM

applications, and growth that resulted in establishment of leading companies in the AM market, including Stratasys (established by Scott Crump), Z Corporation (established by MIT graduate students based on Sachs' technology), and 3D Systems (Figure 3).

Small but Significant Government Role in the Development of the AM Field

The U.S. Government has played a small role in directly supporting AM patents that was critical in the early development of the AM field in the United States. After further analysis of the four foundational processes patented (Table 3) and two NSF-impacted processed patented (Table 4), the government's role was observed across three areas:

- Direct funding for developing early phases of the technology and later refinements in two of the four processes. NSF played a role in four of the six cases. In three of the processes—powder-bed fusion, binder jetting, and contour crafting (sheet lamination)—direct NSF funding supported the early R&D of the processes only after the inventors developed their initial prototypes. NSF funding included awards through the Small Business in Innovation and Research (SBIR) program and the Strategic Manufacturing (STRATMAN) Initiative. However, inventors, particularly those of powder-bed fusion and binder jetting, also leveraged investments from the academic and private sectors to improve upon and later commercialize their technologies. The government did not directly support the other two foundational patents, vat photopolymerization and material extrusion, which were fully developed by the private sector.

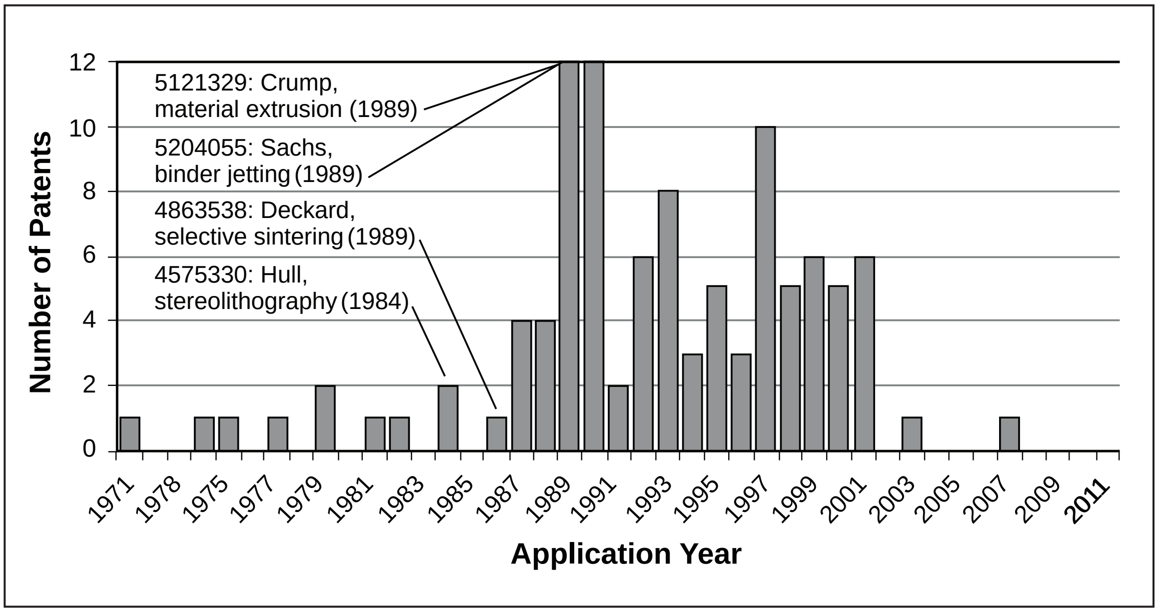


Figure 3. Top 100 U.S. Patents in AM, Including Four Foundational Patents

Table 3. Four Foundational AM Processes and the Federal Role

AM Process	Federal Role Direct NSF Funding	Early Research	Knowledge Diffusion
Vat photopolymerization	None	Influenced by research, researcher later sponsored by DARPA	DOD, Navy/ONR, Air Force, DOE, and NSF supported diffusion of invention
Powder bed fusion	Early funding (e.g., seed funding) supported initial technology development Awards (e.g., small business and research awards) funded technology improvements	Influenced by work sponsored by DOD, Navy /ONR, and Air Force	DOE, DOD, Navy/ONR, Air Force, DARPA, NSF, NASA, and NIST supported diffusion of invention
Material extrusion	None	Influenced by work sponsored by DARPA and Deckard (possibly NSF supported)	DOD, Navy /ONR, NSF, NIH, and NASA supported diffusion of invention
Binder jetting	Role in early development; but only after a prototype was established Funding supported MIT graduate students and theses research Awards closely align with the time period of filing patents Support in later developments and improvements	Influenced by earlier research sponsored by NSF, Navy/ONR, Army, and DARPA	Army, Navy/ONR, DARPA, DOE, NSF, NASA, NIST, and NIH supported diffusion of invention

DARPA, Defense Advanced Research Projects Agency; DOC, Department of Commerce; DOE, Department of Energy; HHS, Department of Health and Human Services; NASA, National Aeronautics and Space Administration; NIH, National Institutes of Health; NIST, National Institute of Standards and Technology; NSF, National Science Foundation; ONR, Office of Naval Research.

Table 4. Two NSF-Impacted Processes and Federal Role

AM Process	Direct Funding
Sheet lamination	DOE seed funding Two NSF small business awards supported the design and testing of an automated machine
Contour crafting	Three NSF research awards supported early research and later developments Navy/ONR, Army, and NASA funding supported later developments

- Support of early research that created the knowledge, technologies, and tools later adopted in the AM field and applied by inventors to develop foundational AM patents and technologies. The knowledge generated from federally sponsored R&D from the early 1970s influenced the patents filed in the 1980s and 1990s and later innovations. Observations from the backwards citations analysis of the foundational patents show that some of the earliest investors in AM were the Department of Defense Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA), which provided steady, continual streams of funding for both academic and industry-based researchers. NSF support was also instrumental in the development of early relevant AM research in the 1970s.

- Support of knowledge diffusion from the foundational patents to improve the technologies and develop new applications. The government leveraged and sponsored technologies stemming from the four foundational patents. For instance, in binder jetting, NSF supported patents stemming from the original patent and those developed by co-inventors for later applications of the technology, such as in tissue regeneration and medical devices.

NSF's Support for Research, Technologies, Networking, and Coordination Activities

NSF has provided almost 600 grants for AM research and other activities over the past 25 years, amounting to more than $200 million (in 2005 dollars) in funding. The NSF's Directorate for Engineering, its Civil, Mechanical and Manufacturing Innovation Division, and its precursors have provided more than two-thirds of those AM grants and more than half of the NSF's total funding support of AM. The Civil, Mechanical and Manufacturing Innovation Division's STRATMAN Initiative provided five early grants amounting to about $3.5 million (in 2005 dollars), and two of the five grants were critical to two foundational patents in the AM field for powder-bed fusion and binder jetting.

Other NSF awards supported education, benchmarking, and roadmapping activities that are critical for the private sector but not funded by industry. Experts interviewed remarked that the 2009 Roadmap for Additive Manufacturing conference co-sponsored by NSF and ONR was an important milestone for defining future research directions for the field, although some in industry felt that industry representation was not large enough. NSF and ONR have also supported student attendance at the Solid Freeform Fabrication Symposium held annually at the University of Texas over the past decade.

Discussion of Lessons for the Government

This research provides lessons for the NSF and other government agencies devoted to supporting knowledge generation and innovation. While the STRATMAN program was well received by the AM community, some of the academic experts interviewed, including those supported by this early program, were critical of the lack of consistency and strategic focus in the NSF's efforts to support AM. To the extent feasible, providing consistent funding with strategic intent would help the NSF sustain its support for emerging areas of science and technology. Providing a consistent strategy at the individual technology level may be difficult to execute, but it merits consideration.

With respect to creating breakthroughs in AM, industrial advances have often been more important than academic research. Of the four foundational AM patents, for example, two were developed within firms without any direct public funding. Analysis of the foundational patents showed that inventors leveraged resources and research from industry, academia, and government to commercialize certain technologies. Networking between industry and academia can be critical for the development of a field and could facilitate identifying areas of common research interests. The government should explicitly support these types of interactions. Funding agencies should support both industry and academia more freely, perhaps through programs that facilitate more seamless university-industry collaboration.

As the case study of contour crafting technology shows, not all AM research found sustained commercial success immediately. Research can also develop in unanticipated directions, eventually proving useful. This is highlighted in potentially ground-breaking work in large-scale construction and the growing application of AM in the manufacturing of aerospace and biomedical devices. The role of serendipity in research, as well as external factors such as new business models, standardization, and patent expiration, should not be underestimated. Therefore, government agencies should focus both on supporting the immediate application of research as well as a range of technological readiness levels with commercial potential in both the near and long terms.

The U.S. Government funded not only AM research in academia but also innovative small firms, conferences, roadmaps, standards development, and student training. Experts underscored the importance of this ancillary support, particularly the training of students who go on to work and innovate in the private sector. Case studies show that several NSF-funded graduate students played a critical role in the development of laser sintering and binder jetting research and patents. Government agencies should support the broader R&D ecosystem by facilitating expertise among students, encouraging start-ups, contributing to prioritization and planning, and helping create a community in the emerging AM field.

While the momentum of the past few years may suggest to some that AM has "arrived," the recent AM roadmap effort has revealed that such challenges as bringing down costs, developing new materials, furthering efforts for consistency and standardization, developing new computer-aided-design tools, educating engineers, increasing process speeds, and advancing biological AM (Bourell, Leu, and Rosen 2009) must be overcome before the technology can become mainstream. The federal government in general and the NSF in particular have an important role in each of these areas.

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The original article was published in *3D Printing and Additive Manufacturing Journal*, December 2014.

"U.S. Federal Investment in the Origin and Evolution of Additive Manufacturing: A Case Study of the National Science Foundation"

http://online.liebertpub.com/doi/abs/10.1089/3dp.2014.0019

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Selected Other Nominations

Four additional publications were called out by the Welch Award Selection Committee as being particularly noteworthy among the non-finalist papers for their high-quality research and success in in the open literature. The variety of professional publications in which IDA researchers' articles have appeared.

In "Cost Growth, Acquisition Policy, and Budget Climate," published in the *U.S. Senate Permanent Subcommittee on Investigations, Committee on Homeland Security and Government Affairs, Staff Report, Defense Acquisition Reform: Where Do We Go From Here?*, October 2014, IDA Researcher **David McNicol** observed that acquisition policy and process have had no sustained influence on weapon system cost growth. Further, the best indicator of future cost growth is the budget climate at Milestone B/II: the percentage cost growth is 3 to 5 times as great in times when the budgets are "tight" or constraining at MS B/II than at other times. The original paper can be found here: http://www.dtic.mil/docs/citations/ADA610317

Dr. McNicol is a Research Staff Member in IDA's Cost Analysis and Research Division. He holds a Doctor of Philosophy in economics/finance from the Massachusetts Institute of Technology.

An article by IDA researcher **Jeremy Teichman**, "Measurement of Gradient Index Materials by Beam Deflection, Displacement, or Mode Conversion," published in *Optical Engineering,* November 2013, describes methods that exploit knowledge of the relationship between refractive index distribution and ray paths to estimate the refractive index distribution based on laser beam deflection, displacement, and mode conversion on passage through the media. The work covers axial, radial (cylindrical), and spherical refractive index distributions. The original article can be found here: http://opticalengineering.spiedigitallibrary.org/article.aspx?articleid=1734392

Dr. Teichman is a Research Staff Member in IDA's Science and Technology Division. He holds a Doctor of Philosophy in mechanical engineering from the Massachusetts Institute of Technology.

IDA researchers **Lance Joneckis, Corinne Kramer, David Sparrow,** and **David Tate** investigated how terrain affects connectivity in mobile ad hoc networks (MANET) in "Modeling Terrain Impact on MANET Connectivity," published in the *Institute for Electrical and Electronics Engineers (IEEE) Military Communications Conference (MILCOM) Proceedings*, November 2014. Both average pairwise link closure and the rate at which the link-state changes when nodes move depend on the characteristics of the intervening terrain. Even though these key parameters depend only mildly on internode distances in common real-world terrains, empirical analysis finds that the number of connected components in the network and the probability of being fully connected are not well-predicted by the average link probability in some terrains. This finding has implications for the limits of ad hoc connectivity under unconstrained maneuver. The original article can be found here: http://dx.doi.org/10.1109/MILCOM.2014.229

Dr. Joneckis is a Research Staff Member in IDA's Science and Technology Division. He holds a Doctor of Philosophy in physics from the University of Maryland.

Dr. Kramer is an Assistant Director in IDA's Science and Technology Division. She holds a Doctor of Philosophy in physics from the Johns Hopkins University.

Dr. Sparrow is a Research Staff Member in IDA's Science and Technology Division. He holds a Doctor of Philosophy in physics from the Massachusetts Institute of Technology.

Dr. Tate is a Research Staff Member in IDA's Cost Analysis and Research Division. He holds a Doctor of Philosophy in operations research from Cornell University.

In their article "Reliability Growth Planning Based on Essential Function Failures," published in the *Institute for Electrical and Electronics Engineers (IEEE) Xplore*, January 2014, IDA researchers **Jonathan Bell** and **Steven Bearden** describe an innovative approach to reliability data collection they developed. This approach would provide greater confidence in the results provided to acquisition officials without increasing test duration. The proposed method of collecting data on essential function failures would also provide more information on system reliability problems, which, if corrected, would help to reduce long-term operating costs, an important objective of the DoD initiatives on improving reliability performance. The original article can be found here: http://dx.doi.org/10.1109/RAMS.2014.6798464

Dr. Bell is a Research Staff Member in IDA's Operational Evaluation Division. He holds a Doctor of Philosophy in materials science and engineering from the University of Illinois at Urbana-Champaign.

Dr. Bearden is an Adjunct Research Staff Member in IDA's Operational Evaluation Division. He holds a Doctor of Philosophy in engineering from Louisiana Tech University.

Past IDA Research Notes Welch Award Issues Recognizing IDA's Best in the Open Literature

The 2014 Winner – "Novel Approach for Analyzing Radar Tracking Residuals" by **Carl Gaither, Dawn Loper, Chris Jackson,** and **Jasmina Pozderac.**

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- "Case Study on Race-Based Al-Qaeda Defections" in Mali by **Jessica Huckabey**
- "Competitive Contracting in the Services Sector" by **Susan Rose, Laura Williams,** and **Andrew Rehwinkel**
- "Evaluating Highly Heterogeneous Document Collections" by **Arun Maiya, John Thompson, Francisco Loaiza-Lemos,** and **Robert Rolfe**
- "Luminescent Spectral Splitting: A New Approach Toward Constructing High-Efficiency Solar Cells" by **John Biddle** and **Brent Fisher**
- "Progress Toward the African Union Continental Early Warning System" by **Alexander Noyes** and **Janette Yarwood**

The 2013 Winner – "Predicted and Measured Multipath Impulse Responses" by **Kent Haspert** and **Michael Tuley**

Finalists

- "Transnational Drug Trade Expansion" in Africa by **Ashley Bybee**
- "Text Classification for Retrieval of Information on Critical Technologies" by **Arun Maiya, Francisco Loaiza-Lemos,** and **Robert Rolfe**
- "Human, Social, Cultural, and Behavioral Modeling for Military Applications" by **Sue Numrich** and **Peter Picucci**
- "Potential Military Conflict Between North and South Korea" by **Kongdan Oh Hassig** and **Ralph Hassig**
- "Estimating Hazardous Releases in Urban Environments" by **Nathan Platt, Steve Warner, Jeffry Urban,** and **James Heagy**
- "Assessing Combat Risk and Compensation" by **Alexander Gallo, Brandon Gould, Maggie Li, Shirley Liu,** and **Stanley Horowitz**
- "Carbon Footprint of Shale Gas by **Christopher L. Weber** and **Christopher Clavin**
- "Effects of Space Debris on Spacecraft" by **Joel Williamsen**

The 2012 Winner – *The Saddam Tapes: The Inner Workings of a Tyrant's Regime 1978-2001* by **Kevin Woods** and co-editors **David Palkki** and **Mark Stout**

Finalists

- "A New Methodology for Estimating Nerve Agent Casualties" by **Deena Disraelly, Terri Walsh, Robert Zirkle,** and **Carl Curling**
- "Rotorcraft Safety and Survivability" by **Mark Couch**
- "Secure Cloud Based Computing" by **Coimbatore Chandersekaran, William Simpson,** and **Ryan Wagner**
- "Orbital Maneuver Optimization Using Time-Explicit Power Series" by **James Thorne**
- "Comparison of Predicted and Measured Multipath Impulse Responses" by **Kent Haspert** and **Michael Tuley**

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