

THE EVOLVING BATTLEFIELD

In recent years, physics and other sciences have contributed extensively to an emerging national-security goal that “for every desired battlefield outcome there should be a precise and well-defined action.”

Since before World War II, the US military has been benefiting from an accelerating cascade of scientific and technological advances: turbojet engines, radar, nuclear weapons, missiles, computers, high-resolution sensors, navigation aids, satellites—a continuing and expanding list. These capabilities revolutionized the effectiveness of military forces in their day. But, over the past two decades, we have seen a new revolution in the precision of military capabilities, once again underwritten by science and technology: precision weapons, precision navigation, precision surveillance, and precision command and control.

Precision plays a key role in the present reality and future expectations of military force application. Achieving a desired precise outcome requires precision across a spectrum of activities ranging from geopolitical judgments to weapons accuracy. Much of what one needs for improving geopolitical judgment is, of course, beyond the purview of science. But even there, the products of science and technology make important contributions. Nonetheless, we focus here primarily on the contributions of science and technology to achieving the desired result against military targets, and on the need for their future contributions to improving precision in selecting and engaging such targets.

The evolution of precision

The implications of precision in the application of military force are far-reaching. Scientists have faced a moral dilemma. Their discoveries served to promote important human values, but often at the price of increasingly more destructive weapons that produced not only more combat casualties but also more collateral death and destruction outside battlefields and military targets.

But in the past two decades, the application of science and technology has made possible a dramatic reversal of this baleful trend. In the last five months of World War II,

National defense with maximum precision and minimum unintended damage should be an attractive challenge for scientists seeking to improve the human condition.

John S. Foster and Larry D. Welch

JOHN FOSTER is chairman of the board of Pilkington Aerospace in Garden Grove, California, and chairman of Technology Strategies and Alliances in Burke, Virginia. He has been director of the Lawrence Livermore Laboratory and Defense Research and Engineering. LARRY WELCH is a retired general of the US Air Force and currently is president and CEO of the Institute for Defense Analyses in Alexandria, Virginia.

for example, American bombing raids claimed the lives of almost a million Japanese civilians—not counting Hiroshima and Nagasaki. On one night in March of that final war year, 234 B-29s dropped a thousand tons of incendiary bombs over downtown Tokyo, killing 84 000 people.¹ More than two decades later, in the Vietnam conflict, the US

dropped almost three times as much explosive tonnage as we used in World War II, killing an estimated 365 000 Vietnamese civilians.²

Then in Desert Storm we saw the implications of precision in selecting targets and directing force against them. Every incident of unintended destruction against noncombatants became an object of press, public, and political attention. For the first time, the pursuit of more effective military force was compatible with dramatic reduction of unintended death and destruction. This new capability also became a political imperative.

Meeting the demands of this political imperative has led to ever more demanding standards of precision. In World War II, “daylight precision bombing” was the euphemism for armadas of heavy bombers delivering many hundreds of bombs, with large average errors, in the hope of inflicting significant damage on a military target.

How much have things changed? In World War II, successfully attacking a 60-by-100-foot target required 3000 sorties dropping 9000 bombs with a circular error radius of more than 3000 feet.³ Most of the damage was not to the intended military target but instead to nearby streets and buildings. Today, by “precision” we mean achieving the desired result with a single weapon delivered with high accuracy at the right time to advance the military objective. (See figure 1.) And the standard continues to change. For some years, the goal was to achieve a consistent accuracy of better than 10 meters. Now it is argued that the term “precision” should be reserved for a consistent accuracy of 1 m or less. But precision has to do with a broader range of capabilities than just the spatial accuracy of delivery. The imperative for more precision also extends to “friendly” combat losses.

Reducing the cost to combatants

During the buildup for the Gulf War, estimates of expected US casualties⁴ in ground combat ranged up to 30 000. There was good reason for such estimates. Table 1 provides some historical insight into such an expectation, and contrasts it with the much more benign eventual outcome.⁵

Combat aircraft losses followed a similar pattern.

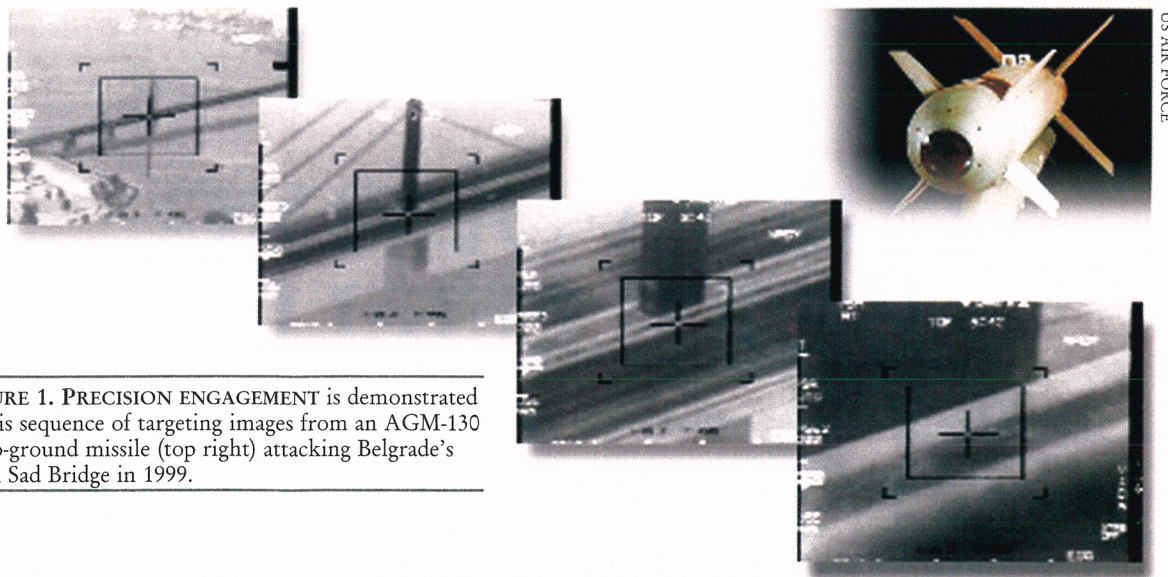


FIGURE 1. PRECISION ENGAGEMENT is demonstrated in this sequence of targeting images from an AGM-130 air-to-ground missile (top right) attacking Belgrade's Novi Sad Bridge in 1999.

Even though US aircraft were facing extraordinary advances in air defenses, our combat planes drastically and continuously cut their losses. By the time of the Kosovo conflict, we could expect very close to zero losses. That expectation became reality as NATO lost only two aircraft and no crew members in some 10 000 attacks against ground targets.⁶

There were many reasons for the drop in casualties among aircrews and ground forces, but prominent among them is the concept of "rapid decisive operations," made possible by scientific and technological innovations. Rapid decisive operations are designed to achieve an operational goal with greatly reduced exposure to risk. Their impact is also evident in table 1, which reminds us how many more sorties were flown in Vietnam, with high cost and questionable success, than in the much more quickly resolved Gulf War.⁷

Regimes of precision

Producing the desired results from precision use of force requires a connected set of "regimes of precision." The capabilities range from battlefield action to concept formulation. The precision regimes range from defining purpose to assessing results and adjusting goals, means, strategy, and tactics. These regimes interact in continuous iteration. Figure 2 illustrates a set of these regimes and the layers of enabling activities they require.

Precision in purpose and objectives is the essential starting point. It has both political and operational dimensions. While acknowledging the importance of the precision in the political aspects, we focus here on the operational dimensions.

An important prerequisite to operational precision is knowing, at the outset, what is likely to be possible and

adjusting to what actually turns out to be possible as the results unfold. Precision in assessing results must serve the purpose of adjusting objectives that prove to have been unrealistic.

Precision will lead to operations in which very agile forces can respond potently within hours to shape the battlespace before the adversary can set the conditions. Interdependent forces will, at first, deploy only essential capabilities to the conflict site, relying on robust communications and precise remote firepower support as needed.

Commanders at all levels will share a continually updated understanding of objectives and the operations of both friendly and enemy forces. The commanders can then act in harmony, quickly and decisively, at a pace that no adversary can match, regardless of his access to commercially available communications and sensors.

Layered surveillance and reconnaissance systems—satellite, airborne, and ground—will provide commanders at all levels with the operating picture most relevant to their situations. Each commander will be able to continually tailor the requisite information for battlespace decisions to meet changing needs. The battlespace will be increasingly dynamic, and static information will quickly become irrelevant.

Lightweight, fuel-efficient vehicles will provide mobility. Units will be able to maneuver rapidly to engage the adversary under conditions controlled and selected by friendly forces. Our forces will operate under a protective shield based on information and agility. They should quickly be able to establish the conditions for operations virtually free of enemy interference. The adversary will be quickly driven to a reactive, defensive mode.

Rapid decisive operations

Science has made possible an impressive array of technologies for enhancing military precision. "Rapid decisive operations" is a useful unifying rubric. It can apply to any battlespace or to other venues, ranging from supporting humanitarian operations to responding to major aggression. Figure 3 illustrates some of the concepts that help us define what is needed from science and technology.

The inner ring in the figure lists very general capabilities required for the achievement of rapid decisive operations:⁸ *Strategic and operational agility* is the abili-

Table 1. US Combat Losses

War	Military deaths	Aircraft losses [†]	Combat sorties	Aircraft lost per sortie
World War II	406 000	18 400	1 747 000	0.95 %
Korea	75 000	605	341 000	0.18 %
Vietnam	59 000	1606	1 992 000	0.081%
Gulf	148	14	29 400	0.048%

[†]Only US Army Air Force and US Air Force.

ty to assemble the needed forces rapidly where they are needed. *Decision superiority* results from having better information than the adversary. It makes possible the operational pace and precision that ensure full control of the situation at the lowest human cost. *Multi-dimensional precision engagement* describes the ability to apply varying levels of appropriate force when and where intended while avoiding unintended consequences such as collateral damage. *Full-dimensional protection* is achieved when our operations can proceed virtually free of enemy interference.

The outer ring of figure 3 lists more specific requirements for implementing the general goals. These specific needs involve technological and scientific challenges. Table 2 lists a number of such specific challenges.

Table 2. Some Challenges for Science and Technology

- ▶ Creating “no-move” zones where airborne and space-based sensors can detect all movement of interest
- ▶ Achieving full capability, all-hours, all-weather air and ground combat operations
- ▶ Extending precision artillery fire beyond the line of sight
- ▶ Seeing through the forest foliage canopy and in urban environments
- ▶ Detecting and neutralizing land mines
- ▶ Providing reliable, jam-resistant, space-based communications and navigation support
- ▶ Managing sensor suites in the battlespace
- ▶ Developing real robotics that can perform real combat tasks

The challenges

▷ “NO-MOVE” ZONES. A no-fly zone has been used effectively in Iraq. This experience suggests the desirability of something broader—a no-move zone that could be enforced against ground vehicles. Such a capability could deter an invasion force. It could also detect and target missile launchers and other mobile weapons that emerge from hiding.

One possibility would be to deploy radar satellites in sufficient numbers to provide almost continuous coverage of areas under scrutiny. The satellites would search for moving targets and then revert to imaging mode to identify an interloper for targeting. In the synthetic-aperture mode, the radar’s wideband waveforms can provide spatial resolution of less than a meter. For good angular resolution, the signal processing would use the radar satellite’s motion to provide differential Doppler shifts at different angles.

This emphasis on detecting movement suggests a new surveillance and intelligence discipline, in addition to the traditional concentration on signals, imaging, measurement, and human intelligence activity. In the dynamic battlespace, “movement intelligence” might well be the most valuable kind of information for commanders. Near real-

time response might be achieved with high-speed ground or air-launched standoff missiles guided by information from the Global Positioning System. That would require either additional onboard sensors or accurate registering of the operations area and accurate update of the GPS coordinates.

▷ AT ALL HOURS, IN ALL WEATHER. For much of the last half century, our opponents owned the night. Night was their time of recovery and repair, because US air and heavy ground forces were largely ineffective in the dark. Furthermore, we were unable to use air power, one of our greatest advantages, in marginal weather. Thus we were disadvantaged more than half the time.

We saw a sharp reversal of such limitations in the Gulf War. But precision night capability is still only available in a limited part of our air and ground force. And precision all-weather capability, provided by highly accurate radar accurately registered to geographic references, is available to only a small fraction of our forces. Over Kosovo, only the half-dozen B-2 bombers provided true all-hours, all-weather precision capability. They achieved the requisite precision by using synthetic-aperture radar to get bearings and range to target. This information was used to update GPS information and the initial measurements. The updated information was given to the weapon that was to be launched and guided to the target.

Although technological solutions already exist, they are expensive and complex. So, once again, we need scientific and technological breakthroughs to provide affordable, lightweight, reliable capabilities. Given the exponential increases in computer processing power and the commercial proliferation of sensors, it should be possible to reduce cost and complexity by at least an order of magnitude, so that true all-weather, all-hours precision strikes become the operational standard.

▷ BEYOND THE LINE OF SIGHT. Historically, tank cannon have provided precision capability within the line of sight. During Desert Storm, for example, US forces repeatedly demonstrated that our tanks could score a high percentage of first-round hits when the target was within sight. But there are compelling reasons for wanting that capability to extend beyond the line of sight.

The Defense Advanced Research Projects Agency (DARPA), the army, the navy, and supporting contractors are pursuing this goal. One approach is a GPS-guided 5-inch artillery round with inertial backup guidance provided by a microelectromechanical system (MEMS) on a chip. Rocket assist provides extended range. The goal is an accuracy of about 10 meters at a range of 100 km. But one needs to reduce sharply the present cost of about \$40 000 per round. We will also need a compatible targeting and

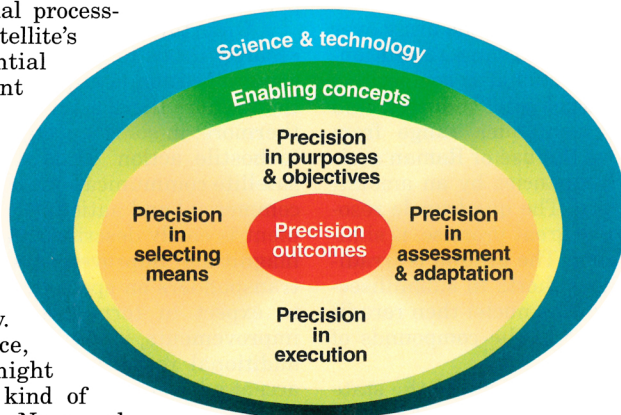


FIGURE 2. PRECISION MILITARY outcomes require various regimes of precision which, in turn, require enabling ideas and technologies.

damage-assessment system.

▷ **THROUGH TREES AND BUILDINGS.** Precision warfare requires the ability to locate targets concealed under heavy foliage or in built-up urban environments. Microwave radars can provide precision location by detecting motion or employing synthetic-aperture modes. But microwave radar suffers high attenuation (of order 99%) when passing through heavy foliage.

At longer wavelengths (UHF and VHF), radar is much better in dealing with foliage. Several such radars on airborne platforms have demonstrated the ability to detect moving and stationary targets under foliage. Figure 4 displays the results of experiments by the Lincoln Laboratory on the probability of detecting and identifying targets from above a forest in Maine at various radar frequencies.

The low frequencies, however, require large antennas to provide range and resolution. Therefore, practical approaches to detecting targets under foliage remain a formidable technical challenge. Furthermore, none of the radar solutions is practicable in urban settings. The urban solution is likely to require combinations of microelectronics, miniature optical systems, and microrobots.

DARPA currently has a program to develop the necessary microrobots. The principal sensor for such tiny vehicles is a silicon CCD electro-optical device with both narrow and wide fields of view, capable of operating in daylight and starlight. Data can either be stored for later readout or transmitted via a communications relay. The robots could navigate by GPS or other means. Propulsion might be provided by miniature fuel cells. Miniaturizing communications and antennas is another substantial challenge.

▷ **FINDING LAND MINES.**

An estimated 100 million land mines are currently deployed around the globe. Each month, these mines claim about 2000 unintended victims. In the Bosnian conflict alone, more than two million mines were laid. These mines continue to constitute a serious threat.

An intensive campaign by DARPA and the army over the past several years has demonstrated some revolutionary techniques. The campaign has included competitive teams made up of people from academia, industry, and government laboratories. The techniques range from using vapor-sensitive polymers to the use of Raman scattering, which shifts the radio frequencies by an amount unique to each chemical structure. The quadrupole resonance technique, which has shown great promise, is similar to magnetic resonance imaging. The ground is irradiated with frequencies of a few megahertz in submillisecond pulses that tip nuclear spins. The nuclei then reradiate at frequencies that are unique to the compounds of interest (such as TNT, PDX, or HMX).

While work on these techniques has moved the state of the art to real possibilities, the scope of the challenge

continues to demand more efficient, reliable, and affordable approaches.

▷ **JAM-RESISTANT COMMUNICATIONS AND NAVIGATION.** Precision military operations will depend critically on making better information available to the decision-maker—at every level from the senior political leadership to the squad leader. This will require reliable, high-bandwidth, readily available communications that can reach anywhere, anytime, with precise information on the location of hostile, friendly, and neutral forces. At present, such a ubiquitous capability depends on space-based support.

For a number of years, an underlying assumption has been that the commercial demand for space-based communications would provide a ready resource for much of our national security needs—even in remote places—and that such capability would be reliable, high-bandwidth, reasonably secure, and reasonably jam resistant. In recent years, however, we have seen trends that may necessitate reassessment. There has been a drastic change in the expectation of growth in demand for commercial communications satellite services. For a rapidly expanding set of applications, new technologies are making fiber optics the preferred approach. It is often cheaper and more reliable, and it is increasingly available where commercial demand is high. Further advances, such as

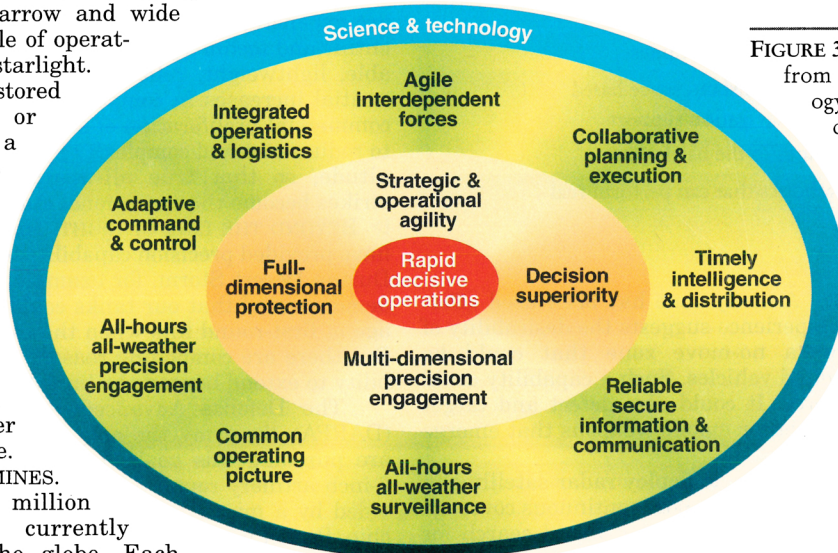


FIGURE 3. WHAT'S NEEDED from science and technology to make rapid, decisive military operations possible. The inner ring categorizes very general goals for whose implementation the outer ring lists more specific requirements.

128-color fiber optics, will only enhance the marketplace preference for fiber optics over satellite communications.

Unfortunately, fiber optics may not serve national security needs in places where wideband, reliable, secure communication is required. We may be operating in locations where there is no entry to a fiber optic system. Furthermore, in some settings, fiber optics can be vulnerable to hostile action. Thus we will need breakthroughs in satellite communications that will serve the needs of both commercial and national-security customers. The requirement is easily described: We will need the same order-of-magnitude improvements in the effectiveness of the transponders on space-based systems that we have come to expect in terrestrial communications. Absent such improvements, we will either have to devote very large additional resources to inefficient systems or we must accept a lower standard of precision application of national power.

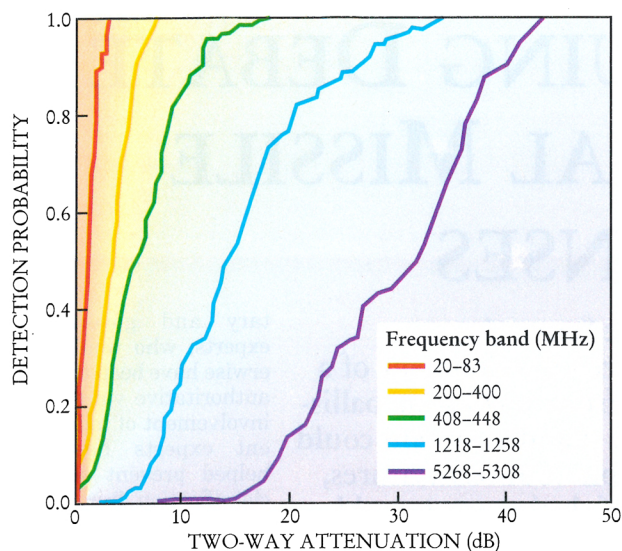


FIGURE 4. THROUGH THE FOLIAGE CANOPY of a Maine forest, a Lincoln Laboratory experiment measured the sensitivity required for target detection by airborne radar in various frequency bands. The higher the frequency, the greater the attenuation of the radar beam as it passes through the canopy on its way down and back. In the highest-frequency band, for example, 80% detection probability would require a radar system sensitive enough to tolerate 38 dB of attenuation. In the lowest-frequency band, by contrast, one could make do with a system capable of tolerating only 2 dB of attenuation, and still get 80% target detection.

▷ **MANAGING SENSOR COMPLEXES.** With the advent of precision guided munitions, the key to precision application of combat power has shifted from lethality to target detection and selection. This will inevitably require layers of distributed sensors. That creates a demand for a new battlespace function: sensor management. Controlling a suite of sensors will require artificial-intelligence algorithms that can assist in rapidly optimizing and reconciling sensor coverage.

Rapid and continuous visualization tools are also needed to assist the human controller. And more reliable automatic target-recognition will be essential to the efficient use of sensor data to direct effective operations.

Extensive experimentation will be needed to learn what works. There will also have to be more powerful human-in-the-loop battlespace simulations, to work out doctrines and procedures, test concepts, rehearse operations, and train operators.

▷ **REAL ROBOTICS FOR REAL COMBAT.** For at least three decades, the promise of robotics has largely been just that: a promise of things to come. Still, important technological advances have been made over a wide range of development paths. For this discussion, we chose to use the broadest definition of robotics. In this context, the purpose of robotics is to perform the many tasks now performed by human combatants that could be performed better or more safely by machines.

Extensive and exciting work is going on in robotics. Let us consider some often overlooked, though widespread, application of robotics already used in combat systems. Modern aircraft flight-control systems, computer-driven stability systems in armored vehicles, and aircraft approach systems are examples of robotics performing tasks better than human combatants and allowing the human to focus on those tasks at which we are better than the machines.

Competitive advantage would seem to be the appropriate criterion for deciding what to attempt with robotics. Humans are generally better than machines at quickly assimilating large amounts of information from a variety of organic and other sensors, and organizing that information for making fast decisions across a wide range of situations. On the other hand, robotics generally has the advantage for relatively simple tasks.

The point is that, for some years to come, robotics will be most useful when it enhances the human capability for

making decisions. In uninhabited air combat vehicles, for example, the robotic system is likely to be most effective and versatile if we take the pilot's brain along, so to speak, and leave the body back on the ground. In fact, for some applications we might use one brain to manage several vehicles; for others we might want several brains for one vehicle.

All this is possible if we can work out how to reliably connect the pilot's brain to the pilotless vehicle. The advantages could be revolutionary. Freed of the need to support and conform to the limitations of the human body, we can have combat systems of unprecedented effectiveness and versatility. We could have surveillance vehicles that stay aloft for a week, or fighter planes that could maneuver at 20 Gs. We could also have miniature systems—about the size of birds or small mammals—that operate freely in urban terrains.

Underlying science and technology

There are still missing pieces needed to provide even the limited set of capabilities described above. Having seen the startling results already achieved in commercial communication, computational science, biochemistry, and other fast-moving technological fields, we believe that the best way to address these national security challenges is to focus the attention of some of the best minds in the world of science and technology on them.

The goal is to support national security interests with the greatest possible precision and the least possible unintended damage. That must surely be an attractive challenge to scientists who would much prefer that their contributions serve to improve the human condition.

References

1. D. M. Kennedy, *Freedom from Fear: The American People in Depression and War 1929-45*, Oxford U. P. (1999), p. 847.
2. S. I. Kutler, ed., *Encyclopedia of the Vietnam War*, Scribner's, New York (1996), p. 103.
3. J. S. Bowman, ed., *Facts About the American Wars*, Wilson, New York (1998) p. 283.
4. J. J. Fialka, A. Pasztor, "Grim Calculus," *The New York Times*, 15 November 1990.
5. J. S. Bowman, ed., *Facts About the American Wars*, Wilson, New York (1998), pp. 409, 492, 597, 648.
6. G. W. Arbogast, *Aerosp. Power J.* **14**, 80 (2000).
7. R. P. Hallion, *Storm Over Iraq, Air Power and the Gulf War*, Smithsonian Institution Press, Washington, D.C. (1992) p. 196.
8. Joint Chiefs of Staff, *Joint Vision 2010 and Joint Vision 2020*, <http://www.dtic.mil/jv2020/jvpub2.htm>