The New Era of Counterforce

Technological Change and the Future of Nuclear Deterrence

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Nuclear deterrence is based on the threat of retaliation. A nuclear arsenal designed for deterrence must, therefore, be able to survive an enemy first strike and still inflict unacceptable damage on the attacker. For most of the nuclear age, the survivability of retaliatory forces seemed straightforward; "counterforce" attacks—those aimed at disarming the enemy's nuclear forces—appeared impossible because the superpower arsenals were large and dispersed, and were considered easy to hide and protect.[1] Today, analysts tend to worry more about the dangers of nuclear terrorism or accidents than the survivability of retaliatory arsenals.[2] Nuclear deterrence appears robust.

Changes in technology, however, are eroding the foundation of nuclear deterrence. Rooted in the computer revolution, these advances are making nu-

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1. See Robert Jervis, *The Meaning of the Nuclear Revolution: Statecraft and the Prospect of Armageddon* (Ithaca, N.Y.: Cornell University Press, 1989), p. 10; Spurgeon M. Keeny Jr. and Wolfgang K.H. Panofsky, "Nuclear Weapons in the 1980s: MAD vs. NUTS," *Foreign Affairs*, Vol. 60, No. 2 (Winter 1981/82), pp. 287–304; Harold Feiveson and Frank von Hippel, "The Freeze and the Counterforce Race," *Physics Today*, Vol. 36, No. 1 (January 1983), pp. 36–49; Robert Jervis, *The Illogic of American Nuclear Strategy* (Ithaca, N.Y.: Cornell University Press, 1984); Charles L. Glaser, "Why Do Strategists Disagree about the Requirements of Strategic Nuclear Deterrence?" in Lynn Eden and Steven E. Miller, eds., *Nuclear Arguments: Understanding the Strategic Nuclear Arms and Arms Control Debates* (Ithaca, N.Y.: Cornell University Press, 1989), pp. 109–171, especially pp. 134–142; and Michael Salman, Kevin J. Sullivan, and Stephen Van Evera, "Analysis or Propaganda? Measuring American Strategic Nuclear Capability, 1969–88," in Eden and Miller, *Nuclear Arguments*, pp. 172–263.

2. On accidents, see Eric Schlosser, *Command and Control: Nuclear Weapons, the Damascus Accident, and the Illusion of Safety* (New York: Penguin, 2013); and Scott D. Sagan, *The Limits of Safety: Organizations, Accidents, and Nuclear Weapons* (Princeton, N.J.: Princeton University Press, 1993). On nuclear terrorism, see Graham Allison, *Nuclear Terrorism: The Ultimate Preventable Catastrophe* (New York: Owl, 2004); but also John Mueller, *Atomic Obsession: Nuclear Alarmism from Hiroshima to Al-Qaeda* (New York: Oxford University Press, 2010); and Keir A. Lieber and Daryl G. Press, "Why States Won't Give Nuclear Weapons to Terrorists," *International Security*, Vol. 38, No. 1 (Summer 2013), pp. 80–104.

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clear forces around the world far more vulnerable than before. In fact, one of the principal strategies that countries employ to protect their arsenals from destruction, hardening, has already been largely negated by leaps in the accuracy of nuclear delivery systems.[3] A second pillar of survivability, concealment, is being eroded by the revolution in remote sensing.[4] The consequences of pinpoint accuracy and new sensing technologies are numerous, synergistic, and in some cases nonintuitive. Taken together, these developments are making the task of securing nuclear arsenals against attack much more challenging.

To be clear, nuclear arsenals around the world are not becoming equally vulnerable to attack. Countries that have considerable resources can buck these trends and keep their forces survivable, albeit with considerable cost and effort. Other countries, however—especially those facing wealthy, technologically advanced adversaries—will find it increasingly difficult to secure their arsenals, as guidance systems, sensors, data processing, communication, artificial intelligence, and a host of other products of the computer revolution continue to improve.[5]

The growing vulnerability of nuclear forces sheds light on an enduring theoretical puzzle of the nuclear age. According to one of the leading theories of geopolitics in the nuclear era, the "theory of the nuclear revolution," nuclear weapons are the ultimate instruments of deterrence, protecting those who possess them from invasion or other major attacks.[6] Yet, if the theory is correct—that is, if nuclear weapons solve countries' most fundamental security problems—why do nuclear-armed countries continue to perceive serious threats from abroad and engage in intense security competition? Why have the great powers of the nuclear era behaved in many ways like their predecessors from previous centuries: by building alliances, engaging in arms races, competing for relative gains, and seeking to control strategic territory—none of which should matter much if nuclear weapons guarantee one's security? Al-

3. "Hardening" here refers to the deployment of nuclear forces (such as delivery systems, warheads, and command sites) in reinforced structures that are difficult to destroy.
4. "Concealment" here refers to efforts to prevent adversaries from identifying or locating one's forces (such as through the use of camouflage, decoys, and especially mobility).
5. For an earlier analysis of the consequences of technological trends in the U.S.-Russia case, see Keir A. Lieber and Daryl G. Press, "The End of MAD? The Nuclear Dimension of U.S. Primacy," *International Security*, Vol. 30, No. 4 (Spring 2006), pp. 7–44; and Keir A. Lieber and Daryl G. Press, "The Rise of U.S. Nuclear Primacy," *Foreign Affairs*, Vol. 85, No. 2 (March/April 2006), pp. 42–54.
6. According to Robert Jervis, the deterrence implications of invulnerable nuclear arsenals are "many and far-reaching": war should not occur, crises will be rare, and the status quo will be relatively easy to maintain. Jervis, *The Meaning of the Nuclear Revolution*, p. 45. Two of the most important works on the theory of the nuclear revolution are Kenneth N. Waltz, "Nuclear Myths and Political Realities," *American Political Science Review*, Vol. 84, No. 3 (September 1990), pp. 731–745; and Jervis, *The Meaning of the Nuclear Revolution*.

though proponents of the theory of the nuclear revolution acknowledge this anomalous behavior, they attribute it to misguided leaders, bureaucratic pathologies, or dysfunctional domestic politics, not flaws in the theory itself.[7]

Our analysis offers a simpler explanation for the disjuncture between the theory of the nuclear revolution's predictions and the foreign policy behavior of states: geopolitical rivalry remains logical in the nuclear age because stalemate is reversible. For nuclear weapons to revolutionize international politics—that is, to render countries fundamentally secure—the condition of stalemate must be enduring. Arsenals that are survivable today, however, can become vulnerable in the future. Nuclear-armed states thus have good reason to engage in intense competition, even if their own arsenals are currently secure.[8] Stated differently, nuclear weapons are the best tools of deterrence ever created, but the possibility of acquiring disarming strike capabilities—and the fear that an opponent might do the same—explains why nuclear weapons have not transformed international politics.[9]

The increasing vulnerability of nuclear forces also has several implications for nuclear policy. First, if nuclear forces are becoming easier to attack, then all else being equal, nuclear-armed states need to deploy more capable retaliatory arsenals to counter the growing risks. Whether one believes that a deterrent force must present potential attackers with "near-certain retaliation," "likely retaliation," or some other level of risk, improvements in counterforce systems require that retaliatory forces adapt—through better capabilities, increased numbers, or both—to maintain the same level of deterrent threat. Furthermore, the rapid rate of change in counterforce technologies increases uncertainty about adversaries' future capabilities, suggesting that countries will need to retain diverse retaliatory forces as a hedge against adversary breakthroughs.

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7. Both Waltz and Jervis criticized the United States and the Soviet Union during the Cold War for being excessively concerned with changes in the military balance of power; for building vast arsenals and seeking nuclear superiority; and for competing hard for allies and strategic territory in the developing world. They (and others) attributed this behavior to the failure of policymakers to appreciate the implications of the nuclear revolution. Jervis, for example, titled his book *The Illogic of American Nuclear Strategy* because, according to him, U.S. policy "seeks to repeal the nuclear revolution rather than coming to grips with [it]." Jervis, *The Illogic of American Nuclear Strategy*, p. 147. See also Waltz, "Nuclear Myths and Political Realities"; Charles L. Glaser, *Analyzing Strategic Nuclear Policy* (Princeton, N.J.: Princeton University Press, 1990); and Stephen Van Evera, *Causes of War: Power and the Roots of Conflict* (Ithaca, N.Y.: Cornell University Press, 1999).

8. As John J. Mearsheimer noted about the Cold War competition: "The continuation of the arms race was not misguided, even though nuclear superiority remained an elusive goal. In fact, it made good strategic sense for the United States and the Soviet Union to compete vigorously in the nuclear realm, because military technology tends to develop rapidly and in unforeseen ways." Mearsheimer, *The Tragedy of Great Power Politics* (New York: W.W. Norton, 2001), p. 231.

9. We explore two other sources of the discrepancy between theoretical expectations and the foreign policies of nuclear-armed states in a forthcoming book manuscript.

Second, the increasing vulnerability of nuclear arsenals raises questions about the wisdom of future nuclear arms reductions. For decades, engineers have toiled to improve weapons accuracy and remote sensing capabilities. Meanwhile, arms negotiators have devised agreements to reduce nuclear arsenals, with the consequence of reducing the number of targets an attacker must destroy in a disarming strike. Either endeavor—improving weapons or cutting stockpiles—can be defended as a policy for promoting strategic stability, but taken together they are creating underrecognized vulnerabilities. The danger of nuclear arms cuts is exacerbated by improvements in nonnuclear means of attacking nuclear forces: for example, through precision conventional strike, missile defense, anti-submarine warfare (ASW), and cyber operations.[10]

Third, the emergence of a new era of counterforce raises the question of whether it is wise, for the United States in particular, to continue improving nuclear and nonnuclear counterforce capabilities. On the one hand, improved counterforce capabilities could be invaluable in a range of plausible scenarios.[11] Improved offensive capabilities could help the United States deter weak countries from initiating conventional conflicts or from escalating in the midst of war. Enhanced counterforce capabilities could also help protect U.S. forces, allies, and the U.S. homeland from nuclear attack if a conventional war did escalate. On the other hand, better counterforce could be a source of danger: not only might improved disarming strike capabilities—in any country's hands—increase the temptation to attack, but also potential victims of disarming strikes will seek to escape their vulnerability, thereby possibly triggering arms racing and incentives to strike preemptively.[12]

Both views may be correct. The net benefit of decisions to enhance counterforce capabilities will therefore depend on the particular case. For countries that perceive a highly malign threat environment, face aggressive nuclear-

10. Arms controllers may respond that one merely needs to restrict the development of advanced counterforce systems, and then arms cuts will be safe again. The technological developments that we describe below, however, especially in accuracy and remote sensing, are so integral to modern conventional warfare that they will be difficult to halt.

11. On the value of effective counterforce, see Keir A. Lieber and Daryl G. Press, "The Nukes We Need: Preserving the American Deterrent," *Foreign Affairs*, Vol. 88, No. 6 (November/December 2009), pp. 39–51; and Keir A. Lieber and Daryl G. Press, "Coercive Nuclear Campaigns in the 21st Century: Understanding Adversary Incentives and Options for Nuclear Escalation," report number 2013-001 (Monterey, Calif.: Project on Advanced Systems and Concepts for Countering Weapons of Mass Destruction, U.S. Naval Postgraduate School, March 2013).

12. For a recent discussion of the dangers of first-strike capabilities, see Charles L. Glaser and Steve Fetter, "Should the United States Reject MAD? Damage Limitation and U.S. Nuclear Strategy toward China," *International Security*, Vol. 41, No. 1 (Summer 2016), pp. 49–98, at pp. 52–53, 92–97.

armed adversaries, or have ambitious foreign policy goals, the benefits of developing advanced counterforce capabilities may outweigh the costs. For those countries that face a benign environment and have more modest goals, however, the secondary costs of enhancing counterforce may be too great. In any case, these contentious issues have not received sufficient attention; analysts and policymakers have largely overlooked the ways that rapidly changing technologies are eroding the foundation of deterrence.

The remainder of this article is organized as follows. We first discuss the key role that arsenal survivability plays in nuclear deterrence theory. Second, we describe the main strategies that planners employ to ensure arsenal survivability in practice. Next, we explore one of the major technological trends eroding survivability, the great leap in weapons accuracy, and illustrate how improved accuracy creates new possibilities for counterforce strikes. We then focus on the second major trend, dramatic improvements in remote sensing, and how the resulting increase in transparency threatens concealed and mobile nuclear forces. We conclude with a summary of our findings and their implications for international politics and U.S. national security.

Nuclear Survivability in Theory

At its core, nuclear deterrence theory rests on two simple propositions. First, countries will not attack their adversaries if they expect the costs to exceed the benefits. Second, nuclear weapons allow countries, even relatively weak ones, to inflict unprecedented levels of damage on those who attack them. Taken together, these propositions suggest that nuclear weapons are the ultimate instruments of deterrence: no conceivable benefit of attacking a nuclear-armed state could be worth the cost of getting hit with nuclear weapons in retaliation. As long as nuclear arsenals are survivable, that is, able to withstand an enemy's first strike and retaliate, nuclear weapons are a tremendous force for peace.

The theory of the nuclear revolution builds on the logic of deterrence theory and extends its implications. Because nuclear weapons make countries fundamentally secure, countries can escape the most pernicious consequences of anarchy. According to the theory of the nuclear revolution, once countries deploy survivable arsenals they no longer need to fear conquest.[13] As a result, they

13. The simple reason for this is that "military victory is not possible." See Jervis, *The Meaning of the Nuclear Revolution*, p. 23. See also Kenneth N. Waltz, *The Spread of Nuclear Weapons: More May Be Better*, Adelphi Paper 171 (London: International Institute for Strategic Studies, 1981); and Van Evera, *Causes of War*, pp. 240–247.

can stop worrying about the relative balance of power;[14] engaging in arms races;[15] or competing for alliance partners and strategic territory.[16]

Proponents of the theory of the nuclear revolution have always recognized the discrepancy between their theory's predictions and the actual behavior of countries in the nuclear era. The Cold War competition between the United States and the Soviet Union, in particular, is filled with empirical anomalies: extensive arms racing, intense concerns about relative power gains and losses, and competition for allies and control of strategic territory—all occurring at a time when the main adversaries appeared to be invulnerable to disarming strikes.[17] World War III was averted, as nuclear deterrence theory would pre-

14. Adversaries no longer need to worry about shifts in the global economic balance of power or the details of the military balance, because one side's "gain" cannot undermine the fundamental security of other nuclear-armed states. As Waltz writes, "Nuclear weapons can carry out their deterrent task no matter what other countries do." See Waltz, "Nuclear Myths and Political Realities," p. 732. Elsewhere Waltz argues, "Nuclear weapons eliminate the thorny problems of estimating the present and future strengths of competing states and of trying to anticipate their strategies." Kenneth N. Waltz, "The Emerging Structure of International Politics," *International Security*, Vol. 18, No. 2 (Fall 1993), pp. 44–79, at p. 73. Similarly, Stephen Van Evera writes that a condition of mutual second-strike capabilities "clears the 'fog of war' by removing the relevance of the clash of military machines. The calculus of relative capabilities drops from the calculus of war." See Van Evera, *Causes of War*, p. 244. According to Robert Jervis, "If the arguments about the nuclear revolution are correct, there should be only tenuous links between the details of the military balance and political outcomes." See Jervis, *The Meaning of the Nuclear Revolution*, p. 42.

15. As Jervis explains, "When security comes from the absolute capability to annihilate one's enemy, then each side can gain it simultaneously. Neither side need acquire more than a second-strike capability and, if either does, the other need not respond since its security is not threatened." Robert Jervis, "Why Nuclear Superiority Doesn't Matter," *Political Science Quarterly*, Vol. 94, No. 4 (Winter 1979/80), pp. 617–633, at p. 618. According to Waltz, "Nuclear weapons make it possible for states to escape the dynamics of arms racing." See Waltz, "Nuclear Myths and Political Realities," p. 741. Because the ability to destroy all of an adversary's nuclear forces in a first strike is "not technologically feasible," states should not build counterforce weapons (or even defensive systems) aimed at neutralizing each other's retaliatory capability. See Jervis, *The Meaning of the Nuclear Revolution*, p. 10. For Waltz, "Because thwarting a first strike is easy, deterrent forces are quite cheap to build and maintain." See Scott D. Sagan and Kenneth N. Waltz, *The Spread of Nuclear Weapons: A Debate Revisited* (New York: W.W. Norton, 2003), p. 30. According to their argument, even conventional arms racing no longer makes sense once a state acquires a survivable nuclear arsenal.

16. In the pre-nuclear era, shifting alliances could have great ramifications for national security. When countries gain the security that comes with survivable arsenals, however, they no longer need to pool resources. See Jervis, *The Meaning of the Nuclear Revolution*, pp. 35–36. "Strategically," Waltz writes, "nuclear weapons make alliances obsolete." Waltz, "The Emerging Structure of International Politics," p. 73. Similarly, with a secure nuclear arsenal the gain or loss of territory has little effect on the balance of power or national security. Nuclear weapons can be delivered across vast distances, so nuclear-armed states no longer need to fight over foreign bases, buffer zones, or military resources derived from the possession of territory. As Van Evera writes, secure nuclear deterrents make "geographic assets less significant." See Van Evera, *Causes of War*, p. 245. For other discussions of the relative unimportance of territory in a nuclear world, see Klaus Knorr, *On the Uses of Military Power in the Nuclear Age* (Princeton, N.J.: Princeton University Press, 1966), pp. 86–87; and Jervis, "Was the Cold War a Security Dilemma?" p. 54.

17. As Jervis writes, "Most of the history of American doctrine and war planning has . . . not come to grips with the fundamental characteristics of nuclear politics." See Jervis, *The Meaning of the Nu-*

dict, but the transformation of international politics that advocates of the theory of the nuclear revolution anticipated never materialized. Today, nuclear powers still eye each other's economic power and military capabilities warily; strive for superiority over their adversaries in conventional and nuclear armaments; aim to control strategically relevant areas of land, air, sea, and space; seek to build and maintain alliances; and prepare for war.

The discrepancy between the theory of the nuclear revolution and the behavior of states stems from the theory's misplaced confidence in the survivability of nuclear arsenals.[18] Proponents of the theory believe that nuclear weapons deployed in even moderate numbers are inherently survivable.[19] Moreover, according to the argument, survivability is a one-way street: once a country deploys a survivable arsenal, it will remain that way. Yet, what if survivability is reversible?

If arsenal survivability depends on the uncertain course of technological change and the efforts of adversaries to develop new technologies, states will feel compelled to arms race to ensure that their deterrent forces remain survivable in the face of adversary advances. They will worry about relative gains, because a rich and powerful adversary will have more resources to invest in technology and military forces. They will value allies, which help contribute resources and valuable territory. Moreover, states may be enticed to develop their own counterforce capabilities in order to disarm their adversaries or limit the damage those adversaries can inflict in case of war. In short, if nuclear stalemate can be broken, one should expect countries to act as they always have when faced with military threats: by trying to exploit new technologies

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clear Revolution, p. 8. More recently, Glaser and Fetter argue that U.S. nuclear strategy in the Cold War "was overly competitive, diverging significantly from the policies implied by the powerful logic of the nuclear revolution." See Glaser and Fetter, "Should the United States Reject MAD?" p. 50.

18. Other deterrence literatures that rely on the assumption that nuclear weapons inherently create stalemate should also be reassessed in light of the technological trends benefiting counterforce. For example, classic works by Thomas C. Schelling and Robert Powell (and related works on resolve, signaling, and bargaining) equate nuclear weapons with military stalemate, and use that assumption as a starting point to explore how states gain coercive leverage under such a condition. By assuming that nuclear weapons create military stalemate, their studies overstate the role of resolve and credibility in deterrence outcomes, and underplay the importance of military capabilities. See, for example, Schelling, *Arms and Influence* (New Haven, Conn.: Yale University Press, 1966); and Powell, *Nuclear Deterrence Theory: The Search for Credibility* (Cambridge: Cambridge University Press, 1990).

19. Some proponents, especially Waltz, argue that retaliatory arsenals are very easy to build, deploy, and maintain. See, for example, Waltz and Sagan, *The Spread of Nuclear Weapons*, pp. 20–23, 142–143. Others are more conservative about the requirements, but nonetheless confident that the development of first-strike capabilities is impossible and will be for the foreseeable future. See Jervis, *The Meaning of the Nuclear Revolution*, p. 10; Jervis, *The Illogic of American Nuclear Strategy*; Glaser, *Analyzing Strategic Nuclear Policy*; and Glaser and Fetter, "Should the United States Reject MAD?"

and strategies for destroying adversary capabilities. If arsenals have been more vulnerable than theorists assume, or if survivability and stalemate are reversible, then the central puzzle of the nuclear era—continued geopolitical competition—is no longer a puzzle.

We argue not only that stalemate is reversible in principal, but also that changes in technology occurring today are making all countries' arsenals less survivable than they were in the past. The fear of suffering devastating retaliation will still do much to deter counterforce attacks, but countries will increasingly worry that their adversaries are trying to escape stalemate, and they will feel pressure to do the same. Deterrence will weaken as arsenals become more vulnerable. In extreme circumstances—for example, if an adversary threatens escalation (or begins to escalate) during a conventional war—the temptation to launch a disarming strike may be powerful.[20] In short, in stark contrast to the expectations of the theory of the nuclear revolution, security competition has not only endured, but also will intensify as enhanced counterforce capabilities proliferate.

Nuclear Survivability in Practice

The survivability of retaliatory arsenals has long been a crucial objective of real-world military planning, not just a fertile topic of theoretical analysis. Military planners have employed three basic approaches to protect their countries' nuclear forces from attack: hardening, concealment, and redundancy. In terms of hardening, planners deploy missiles in reinforced silos designed to resist blast, heat, ground shock, and the other effects of nuclear detonations; place aircraft in hardened shelters; create protective sites for patrolling mobile missile launchers; and bury command and control sites, as well as the secure means used to communicate launch orders.

Nuclear planners also rely heavily on concealment. Concealment is the foundation of survivability for mobile delivery systems, such as ballistic missile submarines (SSBNs) or mobile missile launchers (known as "transporter erector launchers," or TELs), both of which hide in vast deployment areas. Aircraft are harder to hide because they require airfields for takeoff and landing, but they too can employ concealment by dispersing to alternate airfields or re-

20. Keir A. Lieber and Daryl G. Press, "The Next Korean War," *Foreign Affairs*, April 1, 2013, https://www.foreignaffairs.com/articles/north-korea/2013-04-01/next-korean-war. For a more general discussion of wartime escalation risks, see Lieber and Press, "Coercive Nuclear Campaigns in the 21st Century"; and Caitlin Talmadge, "Would China Go Nuclear? Assessing the Risk of Chinese Nuclear Escalation in a Conventional War with the United States," *International Security,* Vol. 41, No. 4 (Spring 2017), pp. 50–92.

maining airborne during alerts. Even the most difficult facilities to hide, hardened missile silos or command bunkers, can be concealed using camouflage and decoys.

Finally, redundancy is used to bolster every aspect of the nuclear mission, especially force survivability. Most nuclear-armed states use multiple types of delivery systems and warheads to complicate enemy strike plans and protect against warhead design flaws. They spread their forces and warheads across multiple bases. Moreover, the most powerful nuclear-weapon states employ redundant communication networks, command and control arrangements, and early warning systems.

No single strategy of survivability is ideal, because each entails important trade-offs. Hardening is attractive, but it comes at the price of concealment: for example, it is difficult to hide the major construction entailed in building a nuclear silo. Also, hardened sites are not mobile; once discovered, they remain so.[21] Similarly, concealment comes at the price of hardening. If mobile forces are discovered, they tend to be easy to destroy. Concealment has another significant drawback: it is a "fail deadly" strategy, meaning that if an adversary develops a way to locate one's forces, one's arsenal might go from highly survivable to completely vulnerable almost overnight. Even worse, one might not know that the nuclear balance has shifted in such a calamitous manner.[22] Some countries have adopted operating doctrines that attempt to capitalize on the advantages of both hardening and concealment: China today, for example, appears to plan to disperse its mobile missiles in a nuclear crisis from its peacetime garrisons to remote protective sites.[23] Such approaches capture the

21. Chinese planners assume that their underground nuclear sites have been discovered by the United States because digging is difficult to hide, and because Chinese planners know that the United States is using a wide range of surveillance tools to find the sites. See Wu Riqiang, "Certainty of Uncertainty: Nuclear Strategy with Chinese Characteristics," *Journal of Strategic Studies*, Vol. 36, No. 4 (July/August 2013), pp. 579–614, at pp. 586–587; Li Bin, "Tracking Chinese Strategic Mobile Missiles," *Science and Global Security*, Vol. 15, No. 1 (2007), pp. 1–30, at p. 5; Zhang Yuliang, ed., *Zhanyi xue* [The science of campaigns] (Beijing: National Defense University Press, 2006), pp. 635, 637; and Yu Jixun, ed., *Di'er pao bing zhanyi xue* [The science of Second Artillery campaigns] (Beijing: PLA Press, 2004), p. 302.

22. New historical evidence reveals that technological breakthroughs and innovative naval operations allowed the United States to trail Soviet ballistic missile submarines during periods of the Cold War. The Soviets were unaware of the extent of the vulnerability of their submarines for several years. See Austin Long and Brendan Rittenhouse Green, "Stalking the Secure Second Strike: Intelligence, Counterforce, and Nuclear Strategy," *Journal of Strategic Studies*, Vol. 38, Nos. 1–2 (2015), pp. 38–73; Owen R. Coté Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, R.I.: Naval War College, 2003); and Peter Sasgen, *Stalking the Red Bear: The True Story of a U.S. Cold War Submarine's Covert Operations against the Soviet Union* (New York: St. Martin's, 2009).

23. Wu, "Certainty of Uncertainty," pp. 586–587; Li, "Tracking Chinese Strategic Mobile Missiles," pp. 7–11; Hans M. Kristensen, Robert S. Norris, and Matthew G. McKinzie, *Chinese Nuclear Forces*

benefits of both strategies, but they also pay the costs. For example, China's strategy leaves its forces vulnerable if an attacker has identified its dispersal sites or detects mobile missiles in transit.[24]

Major technological trends are directly undermining these strategies of survivability. Leaps in weapons accuracy threaten nuclear forces that rely on hardening, while an unfolding revolution in remote sensing threatens nuclear forces that depend on concealment. (Another major change since the end of the Cold War, far smaller nuclear arsenals among potential adversaries, weakens the third strategy of survivability: redundancy.)[25] Developing survivable forces is not impossible, but a new age of vulnerability has begun.

Counterforce in the Age of Accuracy

For most of the nuclear age, neither bombers nor ballistic missiles could deliver weapons accurately enough to reliably destroy hardened targets. Too many variables affected the impact point of a bomb—such as the aircraft's speed and altitude; the air defense environment; and atmospheric conditions including wind, temperature, and humidity—for even highly skilled crews to deliver bombs precisely.[26] Long-range ballistic missiles were even less accurate. Although their initial deployment conjured fears of "bolt-from-the-blue" disarming strikes, throughout the 1970s long-range missiles were not accurate enough to destroy fields of hardened silos.[27]

Technological improvements chipped away at the sources of inaccuracy, however. Leaps in navigation and guidance, including advanced inertial sen-

and U.S. Nuclear War Planning (Washington, D.C.: Federation of American Scientists/Natural Resources Defense Council, November 2006), p. 51; and Yu, *Di'er pao bing zhanyi xue*.

24. Redundancy involves trade-offs, too. Building additional command sites, warning systems, or communication systems is expensive and therefore comes at the cost of deploying additional weapons. Furthermore, redundancy may promote complacency, thus undermining survivability.

25. Both global and U.S. nuclear weapons stockpiles have declined about 80 percent since the end of the Cold War and 85 percent from peak levels in the Cold War. See U.S. Bureau of Arms Control, Verification, and Compliance, "Fact Sheet: Transparency in the U.S. Nuclear Weapons Stockpile" (Washington, D.C.: U.S. Department of State, April 29, 2014); Hans M. Kristensen and Robert S. Norris, "Nuclear Notebook: Nuclear Arsenals of the World," *Bulletin of the Atomic Scientists*, n.d., http://thebulletin.org/nuclear-notebook-multimedia; Hans M. Kristensen and Robert S. Norris, "United States Nuclear Forces, 2016," *Bulletin of the Atomic Scientists*, Vol. 72, No. 2 (March 2016), pp. 63–73; and Shannon N. Kile and Hans M. Kristensen, "Trends in World Nuclear Forces, 2016" (Stockholm: Stockholm International Peace Research Institute, June 2016), p. 2.

26. See Michael Russell Rip and James M. Hasik, *The Precision Revolution: GPS and the Future of Aerial Warfare* (Annapolis: Naval Institute Press, 2002), pp. 14–67.

27. For example, the first U.S. intercontinental ballistic missiles (ICBMs) had a median miss distance (called circular error probable, or CEP) that was two or three times worse than that of contemporary bombers. See David Miller, *The Cold War: A Military History* (New York: Thomas Dunne, 1998), appendix 7; and Duncan Lennox, *IHS Jane's Weapons: Strategic 2012/2013* (London: IHS, 2012).

sors with stellar updates, improved the ability of missiles to precisely determine their position in flight and guide themselves, as needed, back on course. Other breakthroughs allowed mobile delivery systems, such as submarines and mobile land-based launchers, to accurately determine their own position prior to launch, greatly improving their accuracy.[28] As a result of these innovations, new missiles emerged in the mid-1980s with far better accuracy than their predecessors, rendering hardened targets vulnerable as never before. For bombers, onboard computers now continuously measure the variables that previously confounded bombardiers. Data on aircraft speed and location are uploaded from the aircraft into the computers of "smart" bombs and cruise missiles, which in turn automatically plot a flight path from the release location to the target. The weapons adjust their trajectory as they fly to remain on course.[29] As a result, bombs and missiles can achieve levels of accuracy unimaginable at the start of the nuclear age.

The leap in munitions accuracy has been showcased repeatedly during conventional wars: videos of missiles and bombs guiding themselves directly to designated targets now appear mundane. Although the effects of the accuracy revolution on nuclear delivery systems are equally dramatic, they have received far less attention, despite huge implications for the survivability of hardened targets.

IMPROVED MISSILE ACCURACY

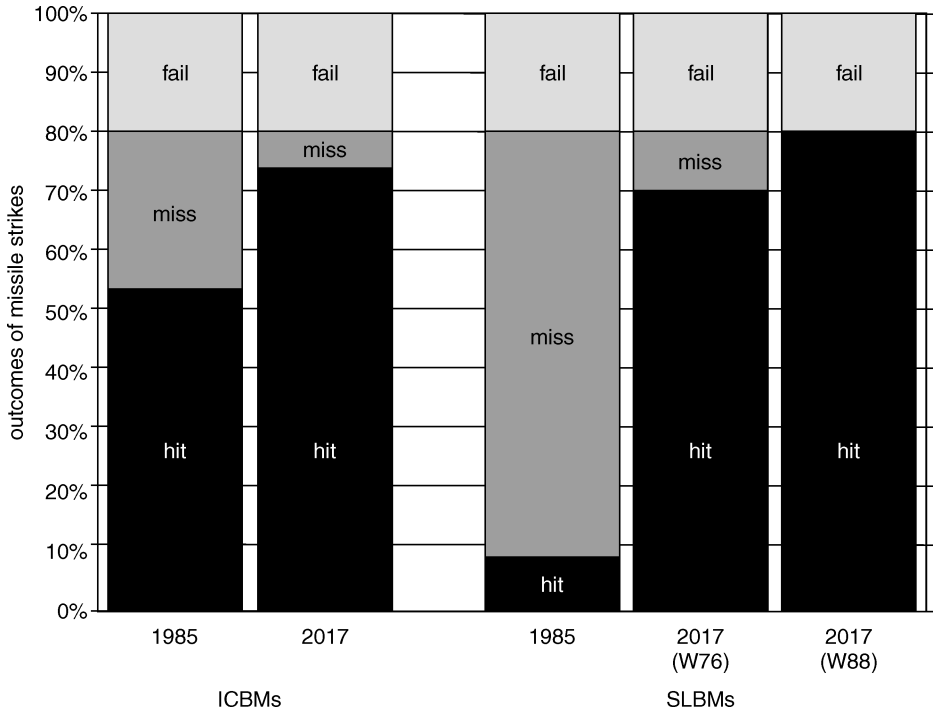
Figure 1 illustrates one consequence of the accuracy revolution, as applied to nuclear forces, by comparing the effectiveness of U.S. ballistic missiles in 1985 to those in the current U.S. arsenal.[30] We use formulas, employed by nuclear analysts for decades, to estimate the effectiveness of missile strikes against a

28. Before submarines used global positioning system (GPS) navigation, ballistic missile accuracy was measured in kilometers. See Rip and Hasik, *The Precision Revolution*, pp. 63, 66.

29. Currently, the two main technologies underlying smart weapons are laser- and GPS-guidance. In the former, a laser is trained on the target, and a computer in the bomb adjusts the tail fins to guide the weapon toward the laser's reflection. In a GPS-guided bomb, a computer on the munition uses GPS to repeatedly assess its location as it falls; the bomb adjusts its tail fins to guide it to a predetermined aimpoint.

30. We focus on U.S. capabilities, but recent versions of Israel's Jericho, India's Agni, Pakistan's Hatf, and Russia's Iskander nuclear-capable missiles employ advanced guidance systems that may outperform even the best contemporary U.S. ballistic missiles described here. See Hans M. Kristensen and Robert S. Norris, "Israeli Nuclear Weapons, 2014," *Bulletin of the Atomic Scientists*, Vol. 70, No. 6 (November 2014), pp. 97–115; "Quiet Leap," *Aviation Week & Space Technology*, Vol. 175, No. 26 (July 2013), p. 1; Hans M. Kristensen and Robert S. Norris, "Indian Nuclear Forces, 2015," *Bulletin of the Atomic Scientists*, Vol. 71, No. 5 (September 2015), pp. 77–83; James C. O'Halloran, *IHS Jane's Weapons: Strategic* (London: IHS, 2015), p. 33; Hans M. Kristensen and Robert S. Norris, "Pakistani Nuclear Forces, 2015," *Bulletin of the Atomic Scientists*, Vol. 71, No. 6 (November 2015), pp. 59–66; and "SS-26 (Iskander)," *MissileThreat* (CSIS Missile Defense Project), September 27, 2016, https://missilethreat.csis.org/missile/ss-26/.

Figure 1. The Growing Vulnerability of Hard Targets, 1985–2017



NOTE: The calculations underlying this figure assume targets hardened to withstand 3,000 pounds per square inch (psi). Data for 1985 are based on the most capable U.S. land-based intercontinental ballistic missile (ICBM) and submarine-launched ballistic missile (SLBM) at the time: the Minuteman III ICBM armed with a W78 warhead and the Trident I C-4 SLBM armed with a W76 warhead. The 2017 ICBM data are based on the same Minuteman III / W78, with an improved guidance system. The 2017 SLBM data show both contemporary configurations of the Trident II D-5 missile: one version armed with the W76 and the other with higher-yield W88 warheads. The data and sources for U.S. weapon systems are in the online appendix, http://dx.doi:10.7910/DVN/NKZJVT, table A1.

typical hardened silo.[31] The figure distinguishes three potential outcomes of a missile strike: hit, miss, and fail. "Hit" means that the warhead detonates within the lethal radius (LR) of the aimpoint, thus destroying the target. "Miss" means that the warhead detonates outside the LR, leaving the target undamaged. "Fail" means that some element of the attacking missile system malfunctioned, leaving the target undamaged.

31. See the online appendix at http://dx.doi.org/10.7910/DVN/NKZJVT. The seminal unclassified work on the effects of nuclear weapons is Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons* (Washington, D.C.: U.S. Government Printing Office, 1977). See also Lynn E. Davis and Warner R. Schilling, "All You Ever Wanted to Know about MIRV and ICBM Calculations

Figure 1 shows that the accuracy improvements of the past three decades have led to substantial leaps in counterforce capabilities. In 1985 a U.S. intercontinental ballistic missile (ICBM) had only about a 54 percent chance of destroying a missile silo hardened to withstand 3,000 pounds per square inch (psi) overpressure. In 2017 that figure exceeds 74 percent. The improvement in submarine-launched weapons is starker: from 9 percent to 80 percent (using the larger-yield W88 warhead). Figure 1 also suggests, however, that despite vast improvements in missile accuracy, the weapons still are not effective enough to be employed individually against hardened targets. Even modern ballistic missiles are expected to miss or fail 20–30 percent of the time. The simple solution to that problem, striking each target multiple times, has never been a feasible option because of the problem of fratricide: the danger that incoming weapons might destroy or deflect each other.[32] The accuracy revolution, however, also offers a solution to the fratricide problem, opening the door to assigning multiple warheads against a single target, and thus paving the way to disarming counterforce strikes.

THE FADING PROBLEM OF FRATRICIDE

One type of fratricide occurs when the prompt effects of nuclear detonations—radiation, heat, and overpressure—destroy or deflect nearby warheads. To protect those warheads, targeters must separate the incoming weapons by at least 3–5 seconds.[33] A second source of fratricide is harder to overcome. Destroying hard targets typically requires low-altitude detonations (so-called ground bursts), which vaporize material on the ground. When the debris begins to cool, 6–8 seconds after the detonation, it solidifies and forms a dust cloud that envelops the target. Even small dust particles can be lethal to incoming warheads speeding through the cloud to the target. Particles in the debris cloud take approximately 20 minutes to settle back to ground.[34]

For decades, these two sources of fratricide, acting together, posed a major

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but Were Not Cleared to Ask," *Journal of Conflict Resolution*, Vol. 17, No. 2 (June 1973), pp. 207–242. These formulas and calculations are also discussed in Lieber and Press, "The End of Mad?" pp. 7–44, and appendix 1.

32. On nuclear fratricide, see John D. Steinbruner and Thomas M. Garwin, "Strategic Vulnerability: The Balance between Prudence and Paranoia," *International Security*, Vol. 1, No. 1 (Summer 1976), pp. 138–181; and Bruce W. Bennett, "How to Assess the Survivability of U.S. ICBMs" (Santa Monica, Calif.: RAND Corporation, 1980), with appendices. For an excellent nontechnical discussion of nuclear fratricide, see Andrew Cockburn and Alexander Cockburn, "The Myth of Missile Accuracy," *New York Review of Books*, November 20, 1980, http://www.nybooks.com/articles/1980/11/20/the-myth-of-missile-accuracy/.

33. A 4-second buffer would separate warheads by approximately 10 kilometers. For an analysis of the targeting issues involved with spacing out warheads, including time of arrival uncertainty, see Bennett, "How to Assess the Survivability of U.S. ICBMs," appendix E, pp. 34–39.

34. John Steinbruner and Thomas Garwin estimate that a reentry vehicle (RV) would collide, on average, with 5 to 10 particles in the range of 3 to 10 grams as it passed through a typical dust

problem for nuclear planners.[35] Multiple warheads could be aimed at a single target if they were separated by at least 3–5 seconds (to avoid interfering with each other); yet, all inbound warheads had to arrive within 6–8 seconds of the first (before the dust cloud formed). As a result, assigning more than two weapons to each target would produce only marginal gains: if the first one resulted in a miss, the target would likely be shielded when the third or fourth warhead arrived.[36]

Improvements in accuracy, however, have greatly mitigated the problem of fratricide. As figure 1 shows, the proportion of misses—the main culprit of fratricide—compared to hits is fading. To be clear, some weapons will still fail; that is, they will be prevented from destroying their targets because of malfunctioning missile boosters, faulty guidance systems, or defective warheads. Those kinds of failures, however, do not generally cause fratricide, because the warheads do not detonate near the target. Only those that miss—that is, those that travel to the target area and detonate outside the LR—will create a dust cloud that shields the target from other incoming weapons. In short, leaps in accuracy are essentially reducing the set of three outcomes (hit, fail, or miss) to just two: hit or fail. The "miss" category, the key cause of fratricide, has virtually disappeared.[37]

The Cumulative Consequences for Counterforce

The end of fratricide is just one development that has helped negate hardening and increased the vulnerability of nuclear arsenals. The computer revolution has led to other improvements that, taken together, significantly increase counterforce capabilities.

First, improved accuracy has transformed the role of ballistic missile submarines, turning these instruments of retaliation against population centers into potent counterforce weapons. Recall (from figure 1 above) that a 1985 submarine-launched ballistic missile (SLBM) had only a 9 percent chance of destroying a hardened target. This meant that although ballistic missile submarines could destroy "soft" targets (e.g., cities), they could not destroy the hardened sites that would be a key focus of a disarming attack. Increased

cloud—any one of which would destroy the RV. See Steinbruner and Garwin, "Strategic Vulnerability," appendix C, p. 178.

35. For a Cold War example, see Salman, Sullivan, and Van Evera, "Analysis or Propaganda?" For a contemporary analysis that makes the same assumption, see Lauren Caston et al., *The Future of the U.S. Intercontinental Ballistic Missile Force* (Santa Monica, Calif.: RAND Corporation, 2014), p. 36, including n. 16.

36. Debris clouds around silos would not prevent missiles from launching. At the relatively slow speeds of early "boost phase," missiles could ascend through particles in the debris cloud.

37. The consequences of the fading problem of fratricide for counterforce are illustrated in table 1.

SLBM accuracy has added hundreds of SLBM warheads to the counterforce arsenal; it has also unlocked other advantages that submarines possess over land-based missiles. For example, submarines have flexibility in firing location, allowing them to strike targets that are out of range of ICBMs or that are deployed in locations that ICBMs cannot hit.[38] Submarines also permit strikes from close range, reducing an adversary's response time. And because submarines can fire from unpredictable locations, SLBM launches are more difficult to detect than ICBM attacks, further reducing adversary response time before impact.

Second, upgraded fuses are making ballistic missiles even more capable than figure 1 reports. In a compelling new analysis, Theodore Postol explores the implications of new "compensating" fuses that exist on most U.S. SLBMs and that will soon be deployed on the entire force.[39] Reentry vehicles equipped with this fusing system use an altimeter to measure the difference between the actual and expected trajectory of the reentry vehicle, and then compensate for inaccuracies by adjusting the warhead's height of burst.[40] Specifically, if the altimeter reveals that the warhead is off track and will detonate "short" of the target, the fusing system lowers the height of burst, allowing the weapon to travel farther (hence, closer to the aimpoint) before detonation. Alternatively, if the reentry vehicle is going to detonate beyond the target, the height of burst is adjusted upward to allow the weapon to detonate before it travels too far.[41] Without this technology, as figure 1 shows, the lower-yield W76 warheads are much less effective against hardened targets than their higher-yield cousins, the W88s. The improved fuse cuts the effectiveness gap roughly in half, making the hundreds of W76s in the U.S. arsenal potent counterforce weapons for the first time.[42] The consequences of the new fuse

38. U.S. ICBMs launched at Russia or China—or vice versa—would take a polar route to their targets. As a result, critical sites could be shielded from ICBMs by locating them on the south side of steep mountains. SLBMs can strike targets from a wide range of launch locations, thwarting efforts to shield them.

39. Theodore Postol, "Monte Carlo Simulations of Burst-Height Fuse Kill Probabilities," unpublished presentation, July 28, 2015. The compensating fuse is reportedly deployed on all SLBMs with Mk-5 RVs (i.e., those armed with W88 warheads) and Mk-4A RVs (i.e., those armed with the recently upgraded W76-1 warheads). The remaining SLBMs with older Mk-4 RVs will be upgraded by 2019. See Kristensen and Norris, "United States Nuclear Forces, 2016," pp. 64, 66, 68; and Sandia National Laboratories, "Defense Programs," *Sandia Weapon Review Bulletin*, Autumn 1992, pp. 3–4.

40. See Postol, "Monte Carlo Simulations of Burst-Height Fuse Kill Probabilities"; Donald A. Price and Charles A. Louis, "Burst Height Compensation," United States Patent US4456202 A, June 26, 1984; and John Ainsle, "Sharpening Trident," *swordofdamocles.org*, 2009, and published sources cited therein.

41. See the online appendix.

42. See ibid. See also Hans M. Kristensen, "Small Fuze, Big Effect," *Strategic Security* blog (Federa-

are, therefore, profound, essentially tripling the size of the U.S. submarine-based arsenal against hard targets.[43] More broadly, the technology at the core of compensating fuses is available to any state capable of building modern multistage ballistic missiles.[44]

A third key improvement, rapid missile retargeting, increases the effectiveness of ballistic missiles by reducing the consequence of malfunctions. As figure 1 illustrates, when accuracy increases, missile reliability becomes the main hurdle to attacks on hardened targets. For decades analysts have recognized a solution to this problem: if missile failures can be detected, the targets assigned to the malfunctioning missiles can be rapidly reassigned to other missiles held in reserve.[45] The capability to retarget missiles in a matter of minutes was installed at U.S. ICBM launch control centers in the 1990s and on U.S. submarines in the early 2000s, and both systems have since been upgraded.[46] We do not know if the United States has adopted war plans that fully exploit rapid reprogramming to minimize the effects of missile failures.[47] Nevertheless, such a targeting approach is within the technical capabilities of the United States and other major nuclear powers and may already be incorporated into war plans.[48]

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tion of American Scientists), March 14, 2007, https://fas.org/blogs/security/2007/03/small_fuze_-_big_effect/.

43. In 2016 the United States reportedly had 768 W76 warheads and 384 W88s. See Kristensen and Norris, "United States Nuclear Forces, 2016," p. 64.

44. Compensating fuses may also enhance the capability of SLBMs to conduct "depressed trajectory" strikes, in which a missile flies along a flatter trajectory, thereby reducing its flight time (and hence the target's warning). In the past, the benefit of depressed trajectory for counterforce strikes was mitigated because flat trajectories eroded accuracy. Compensating fuses, however, allow planners to minimize the deleterious effects of depressed trajectories and thus allow SLBMs to strike hard targets with little warning.

45. Writing in 1976, Steinbrunner and Garwin argued that the threats to U.S. ICBMs were overblown, but they cautioned that if the Soviets developed highly accurate delivery systems (i.e., systems less accurate than U.S. missiles today) and utilized reprogramming, ICBM fields would be highly vulnerable. The technological conditions that they feared have come to pass. Steinbrunner and Garwin, "Strategic Vulnerability," pp. 151–155, 159–168.

46. On the Air Force's Rapid Execution and Combat Targeting (REACT) system and the Navy's SLBM Retargeting System (SRS), see Amy E. Woolf, "U.S. Strategic Nuclear Forces: Background, Development, and Issues" (Washington, D.C.: Congressional Research Service, March 10, 2016), p. 14; Hans M. Kristensen, "U.S. Strategic War Planning after 9/11," *Nonproliferation Review*, Vol. 14, No. 2 (July 2007), pp. 373–390, at p. 382; Andrew S. Kovich, "ICBM Strike Planning," *Association of Air Force Missileers (AAFM) Newsletter*, Vol. 15, No. 2 (June 2007), pp. 6–11; and William M. Arkin, "The Six-Hundred Million Dollar Mouse," *Bulletin of the Atomic Scientists*, Vol. 52, No. 6 (November/December 1996), p. 68.

47. Reprogramming creates complications for war planners. For example, ballistic missile strike plans are orchestrated to prevent incoming weapons from interfering with each other. A plan that fully employed reprogramming to negate missile failures would need to establish two (or more) temporal windows for reentry vehicles to safely approach their targets—one for the warheads on the initial missile assigned to a target and one for the warheads on reserve missiles if the initial missile failed. Planners might also need to employ lofted trajectories for reserve missiles to clear the dust clouds shielding targets that were already struck.

48. Bruce Blair, a former missile launch control officer, testified to the U.S. Congress nearly two de-

Table 1 illustrates the consequences of these improvements against two hypothetical target sets: 100 moderately hard mobile missile shelters and 200 hardened missile silos.[49] Row 1 shows the approximate counterforce capabilities of a 1985-era U.S. Minuteman III ICBM strike; a 2-on-1 attack would have been expected to leave 8 mobile missile shelters intact. A strike against 200 hardened silos would fare worse, with 42 targets expected to survive.

The remaining rows in table 1 highlight the implications of the changes that have occurred from 1985 to 2017. Row 2 illustrates the impact of improved Minuteman III guidance, which reportedly reduced circular error probable (CEP) from 183 to 120 meters. Row 3 employs the most capable missile and warhead combination in the current U.S. arsenal: the Trident II armed with a high-yield W88 warhead. As the results in both rows show, upgraded missiles perform better than their predecessor, but not well enough to conduct effective disarming strikes against large target sets.

Rows 4–7 demonstrate how the various improvements in missile technology have combined to create transformative counterforce capabilities. In row 4, we use a more realistic figure for missile system reliability. Although 80 percent missile reliability is traditionally used as a baseline, much evidence suggests that the actual reliability of modern missiles exceeds 90 percent.[50] Row 4 shows attack outcomes for a Trident II/W88 with 90 percent reliability. Row 5 shows the consequences if the United States can reprogram its mis-

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cades ago that Russia could reprogram its silo-based missiles in 10 seconds. See Blair, testimony before the House Committee on National Security, Subcommittee on Military Research and Development, 105th Cong., 1st sess., March 17, 1997.

49. One hundred moderately hard targets is a plausible estimate of the number of targets that the United States might strike in a disarming attack against North Korea (to hit possible missile shelters, weapon storage, and command and control sites) or in a limited strike on China. Two hundred hardened silos roughly correspond to Russia's fixed ICBM force. See Hans M. Kristensen and Robert S. Norris, "Russian Nuclear Forces, 2015," *Bulletin of the Atomic Scientists*, Vol. 71, No. 3 (May 2015), pp. 84–97; Hans M. Kristensen and Robert S. Norris, "Chinese Nuclear Forces, 2015," *Bulletin of the Atomic Scientists*, Vol. 71. No. 4 (July/August 2015), pp. 77–84; and Office of the Secretary of Defense, *Annual Report to Congress: Military and Security Developments Involving the People's Republic of China* (Washington, D.C.: U.S. Department of Defense, 2015).

50. A group of engineers and scientists with relevant expertise advised us that our 80 percent baseline figure for missile reliability is too low. Indeed, the Trident II boasts a 96 percent success rate. See "Navy's Trident II D5 Missile Marks 155 Successful Test Flights," press release (Bethesda, Md.: Lockheed Martin, February 23, 2015); and "Trident D-5," *Encyclopedia Astronautica*, http://www.astronautix.com/t/tridentd-5.html. The former commander of Russia's Strategic Rocket Forces claims a 92 percent launch success rate for Russian missiles throughout the Cold War; the U.S. Central Intelligence Agency (CIA) estimates the success rate to be slightly higher. On Russia claims and tests, see Pavel Podvig, "History of Missile Launches and Reliability," *Russianforces.org*, January 6, 2005, http://russianforces.org/blog/2005/01/history_of_missile_launches_an.shtml. For CIA estimates, see CIA, "Russian Expectations," February 1, 1993, document 0000382541, CIA FOIA Electronic Reading Room, pp. 9–10, https://www.cia.gov/library/readingroom/document/estimated-pub-date-russian-expectations. Tests cannot simulate the conditions of a wartime missile launch, but a 90 percent reliability figure—which we employ in rows 4–7 of table 1—seems reasonable given this evidence and expert opinion.

Table 1. The Demise of Hard Target Survivability

		Weapon Charateristics				100 Mobile Missile Shelters		200 Hardened Missile Silos	
Description	Weapon	Yield (kt)	CEP (m)	Reliability	Attack Plan	p(K)	Survives	p(K)	Survives
Baseline 1985	Minuteman W78	335	183	0.8	2:1	0.92	8	0.79	42
Baseline 2017	Minuteman W78	335	120	0.8	2:1	0.96	4	0.93	13
	Trident II W88	455	90	0.8	2:1	0.96	4	0.96	8
Realistic reliability	Trident II W88	455	90	0.9	2:1	0.99	1	0.99	2
Reprogramming					2:1R	0.99+	0	0.99+	0
Many on 1					3:1	0.99+	0	0.99+	0
Compensating fuse	Trident II W76	100	90	0.9	2:1R	0.99+	0	0.99	1

NOTE: Results are displayed for 100 mobile missile shelters hardened to withstand up to 1,000 pounds per square inch (psi) or 200 missile silos hardened to 3,000 psi. Yield is in kilotons and circular error probable (CEP) is in meters. The column "Attack Plan" indicates the number of warheads assigned to each target; "R" (for reprogramming) means that the attacker uses reserve missiles to replace boost phase malfunctions. The columns titled "p(K)" list the probability that each individual target is destroyed, and "Survives" is the expected number of targets surviving the attack. The designation of "0.99+" under p(K) indicates 99.9 percent or greater chance of destroying each individual target. Light shaded cells indicate successful disarming attacks; darker cells indicate very successful strikes. Note that a single surviving mobile missile shelter does not necessarily imply that a mobile missile survived, whereas a surviving silo suggests a surviving missile.

siles to replace boost-phase failures. As row 5 reveals, a 2-on-1 attack with reprogramming would be expected to destroy every hardened shelter or silo. Row 6 omits reprogramming, but it demonstrates the impact of the decline in fratricide by adding a third warhead to each target, resulting again in the destruction of either target set.

Row 7 illustrates the impact of compensating fuses. This row, unlike the others, employs the lower-yield warhead on the Trident II missiles (the W76). With the compensating fuse, a 2-on-1 attack using W76s would be expected to destroy all the mobile missile shelters and all but one of the hardened silos. (An attack that mixed W88s and W76s could destroy the entire hardened silo force.)

The results in table 1 are simply the output of a model. In the real world, the effectiveness of any strike would depend on many factors not modeled here, including the skill of the attacking forces, the accuracy of target intelligence, the ability of the targeted country to detect an inbound strike and "launch on warning," and other factors that depend on the political and strategic context. As a result, these calculations tell us less about the precise vulnerability of a given arsenal at a given time—though one can reach arresting conclusions based on the evidence—and more about trends in how technology is undermining survivability.[51]

One crucial consequence of the accuracy revolution is not captured in the above results. Yet, its impact on the vulnerability of nuclear arsenals may be just as profound. The accuracy revolution has rendered low-casualty counterforce attacks plausible for the first time.

THE DAWN OF LOW-CASUALTY COUNTERFORCE

In nuclear deterrence theory, the primary factor preventing nuclear attack is the attacker's fear of retaliation. In reality, however, additional sources of inhibition exist, including the terrible civilian consequences of an attempted counterforce strike. If a leader contemplating a disarming strike knows that such an attack will inflict massive casualties on the enemy, that leader will also understand that the failure to disarm the enemy will provoke a massive punitive response, foreclosing the possibility of a limited nuclear exchange. Furthermore, if a disarming strike would cause enormous civilian casualties in the target country, but also possibly in allied and neutral neighboring countries, leaders who value human life or the fate of allies would contemplate such an

51. In an important respect, our model substantially understates the vulnerability of hard targets, because it does not capture the growing contribution of nonnuclear forces to counterforce missions.

attack in only the direst circumstances. The link between civilian casualties and nuclear inhibition explains why many arms control advocates oppose the development of less destructive nuclear weapons; they worry that such weapons are more "usable."[52]

Counterforce was tantamount to mass casualties throughout the nuclear age, but the accuracy revolution is severing that link. In the past, the main impediment to low-casualty nuclear counterforce strikes has been radioactive fallout. Targeters would have had to rely on ground bursts to maximize destructive effects against hardened facilities such as silos and storage sites. Detonations close to the ground have a major drawback, however: debris is sucked up into the fireball, where it mixes with radioactive material, spreading radiation wherever it settles. Although the other effects of nuclear detonations (e.g., blast and fire) can have large-scale consequences for civilians, in many circumstances those effects can be minimized.[53] If a strike produces fallout, however, the consequences are potentially vast and difficult to predict.[54]

In theory, it has always been possible to employ nuclear weapons without creating much fallout. If weapons are detonated at high altitude (above the "fallout threshold"), very little debris from the ground will be drawn up into the fireball, greatly reducing fallout.[55] In practice, however, this targeting strategy has never been feasible against hardened sites. The problem is that any high-yield weapon that detonates low enough to destroy a hardened target will also be low enough to create fallout. Low-yield weapons could do the job and remain above the fallout threshold, but that has always been impractical because low-yield weapons would need to be delivered with great precision to destroy hardened sites, which was previously impossible.[56]

52. See, for example, Julian Borger, "America's New, More 'Usable,' Nuclear Bomb in Europe," *Guardian*, November 10, 2015. As U.S. Senator Dianne Feinstein recently stated, "The so-called improvements to this weapon [the long-range nuclear cruise missile] seemed to be designed candidly to make it more usable, to help us fight and win a limited nuclear war. I find that a shocking concept. I think this is really unthinkable." Cited in Hans M. Kristensen, "Flawed Pentagon Nuclear Cruise Missile Advocacy," *Strategic Security* blog, June 10, 2016, https://fas.org/blogs/security/2016/06/dod-lrso-letter/.

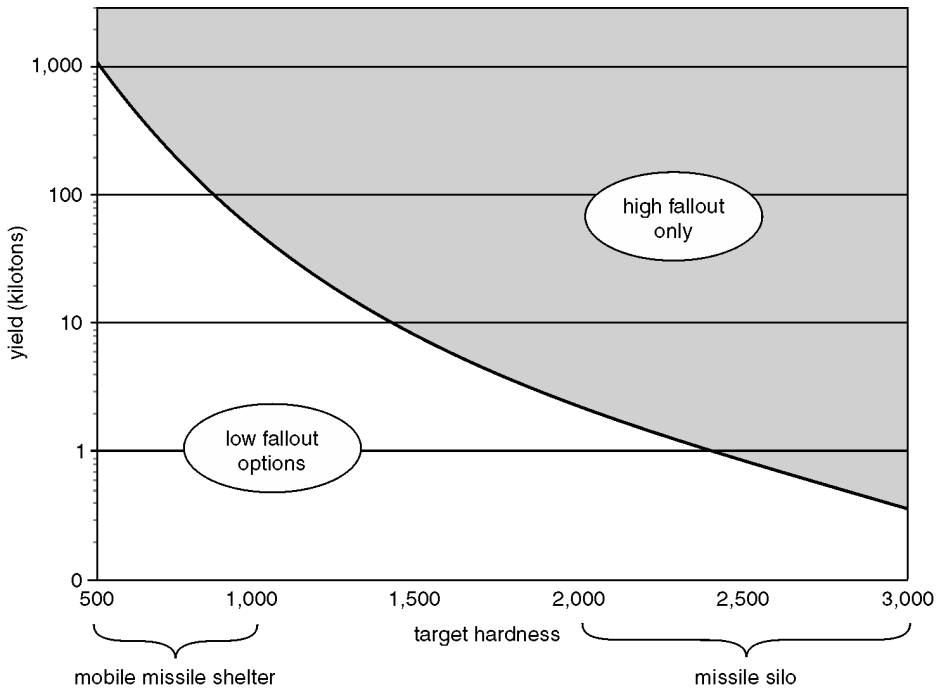
53. If counterforce targets are located outside cities (as most are), targeters can select aimpoints, yields, and heights of burst to minimize the fire and overpressure consequences for civilians. For a study that illustrates the potentially vast consequences of fallout in strategic strikes, see William Daugherty, Barbara Levi, and Frank von Hippel, "The Consequences of 'Limited' Nuclear Attacks on the United States," *International Security*, Vol. 10, No. 4 (Spring 1986), pp. 3–45. On the large-scale consequences of fire and blast, see Lynn Eden, *Whole World on Fire: Organizations, Knowledge, and Nuclear Weapons Devastation* (Ithaca, N.Y.: Cornell University Press, 2004).

54. For example, targeters cannot reliably predict whether wind speed and direction will blow fallout over an unpopulated region or a city.

55. Glasstone and Dolan, *The Effects of Nuclear Weapons*, pp. 36–38; and Office of Technology Assessment, *The Effects of Nuclear War* (Washington, D.C.: U.S. Government Printing Office, 1979), pp. 18, 22–24, 35.

56. See the online appendix for the calculations underpinning these claims and figure 2.

Figure 2. The Potential for Low-Fallout Nuclear Counterforce



NOTE: "Target hardness" (the horizontal axis) is measured in pounds per square inch (psi), with a typical range of psi for hardened mobile missile shelters and missile silos noted. "Yield" (the vertical axis) is measured in kilotons and plotted on a logarithmic scale. The curve depicts the maximum weapon yield that can destroy a given target from above the fallout threshold. Any weapon yield/target hardness combination above the line that is effective enough to destroy the target will necessarily result in fallout. Points below the line indicate that weapons can be detonated at an altitude that will destroy the target yet produce little or no fallout. See the online appendix for calculations.

Figure 2 illustrates why high-yield strikes against hard targets inevitably create fallout, and it highlights the potential low-yield solution to the fallout problem. The vertical axis reflects weapon yield, and the horizontal axis depicts the hardness of potential targets—with the approximate values for mobile missile shelters and missile silos indicated. The solid black line shows the maximum yield of a weapon that can generate enough overpressure to destroy a target from above the fallout threshold. For example, figure 2 shows that for a 3,000 psi target, the highest-yield weapon that can destroy it while remaining above the fallout threshold is 0.35 kilotons. A larger-yield weapon will necessarily cause fallout if it destroys the target. A low-fallout strike against a 1,000 psi mobile missile shelter would require a weapon with 50 kilo-

tons yield, or less. In short, low-fatality nuclear counterforce is possible, but it requires low-yield weapons, and hence very accurate delivery.

The accuracy of nuclear delivery systems is now to the point that low-casualty disarming strikes are possible. For example, a 0.3 kiloton bomb would require a CEP of 10–15 meters to be highly effective against hard targets;[57] that level of accuracy is likely within the reach of the new guided B61-12, which is slated to replace all nuclear gravity bombs in the U.S. arsenal.[58] Similarly, a 5-kiloton missile warhead, which may approximate the yield of the fission primary on many existing ballistic missiles, could destroy a hardened target if its CEP was approximately 50 meters.[59] That level of accuracy was implausible for most of the Cold War, yet it is within reach of many countries today.[60]

By detonating weapons above the fallout threshold, targeters can greatly reduce fallout relative to ground bursts. But how significant are these reductions? How many fewer deaths would be caused in comparison with ground burst strikes?

To compare the fallout and potential fatalities from high-yield and low-yield counterforce operations, we used unclassified U.S. Defense Department software, called Hazard Prediction and Assessment Capability (HPAC).[61] We modeled two different counterforce strikes, one using a "traditional" high-yield approach and one employing low-yield airbursts, against five hardened targets in North Korea (e.g., nuclear storage sites or hardened mobile missile shelters). Because there is no available unclassified information about the location of North Korea's nuclear storage sites, we modeled strikes against notional locations around the DPRK's periphery.

57. See ibid.

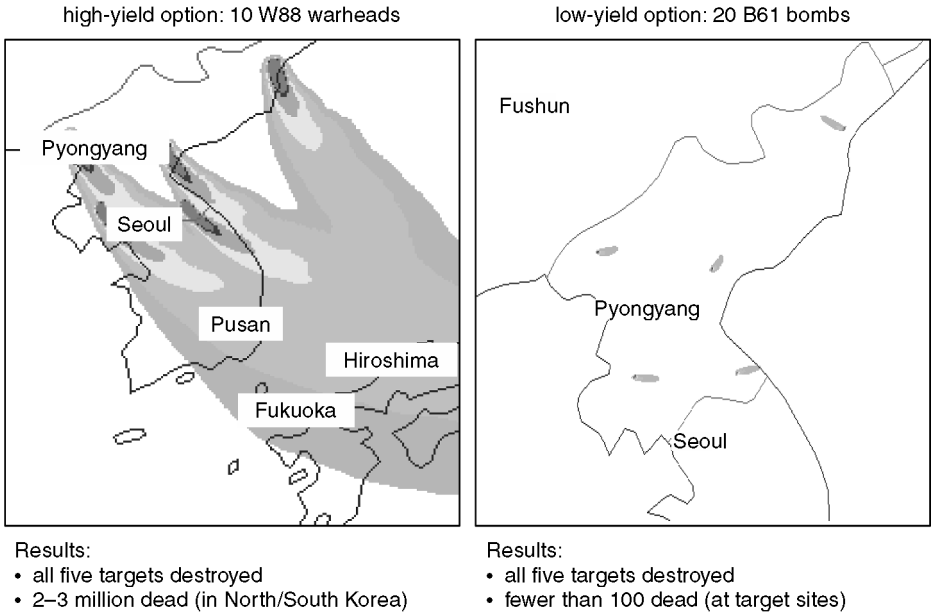
58. The B61-12 is a guided munition that is said to be similar to a conventional Joint Direct Attack Munition (JDAM). JDAMs use inertial navigation and GPS in tandem to guide the bomb to the target. If a JDAM has a clear GPS signal all the way to the target, the CEP is approximately 5 meters. If the GPS signal is not available, accuracy is approximately 30 meters. If the B61-12 uses inertial navigation with in-flight updates from some external source (perhaps GPS), it should have accuracy comparable to that of the JDAM. In fact, in a recent test drop the B61-12 appears to have landed within 15 meters of the aimpoint. See Hans M. Kristensen and Matthew McKinzie, "Video Shows Earth-Penetrating Capability of B61-12 Nuclear Bomb," *Strategic Security* blog, January 14, 2016, https://fas.org/blogs/security/2016/01/b61-12_earth-penetration/; and Hans M. Kristensen, "B61 LEP: Increasing NATO Capability and Precision Low-Yield Strikes," *Strategic Security* blog, June 15, 2011, https://fas.org/blogs/security/2011/06/b61-12/.

59. See the online appendix for these calculations.

60. Several nuclear-armed countries have deployed short- and medium-range ballistic missiles with approximately 50-meter CEP. Although (according to open source data) no intercontinental-range ballistic missiles can achieve 50-meter CEP, compensating fuses may allow existing missiles (with primary-only options) to destroy hardened sites from above the fallout threshold.

61. HPAC allows the user to select the number, yield, altitude, location, date, and time of simulated nuclear detonations, then estimates the amount and pattern of fallout that would likely be generated by the strikes.

Figure 3. Low-Fallout Counterforce Option against North Korea



NOTE: The figure illustrates the potential fallout consequences of two alternative counterforce strikes against five notional North Korean hardened nuclear sites. In both strike options, each target is destroyed with greater than 95 percent probability. The high-yield attack employs ten W88 warheads (455-kiloton yield), with two warheads against each target. Because high-yield weapons cannot destroy hardened sites from above the fallout threshold, the W88s are ground bursts. The low-yield attack uses twenty B61 bombs (0.3-kiloton yield), set to detonate at an altitude that maximizes effectiveness while minimizing fallout. The fallout patterns and casualty figures were generated using unclassified U.S. Defense Department software, called Hazard Prediction and Assessment Capability.

The results of the two strikes, illustrated in figure 3, are starkly different. The traditional approach (on the left side) would likely destroy the targets, but at a terrible price: millions of fatalities across the Korean Peninsula. The low-yield option, by contrast, would produce vastly fewer deaths. As long as the targets were located outside North Korean cities, the number of Korean fatalities from a low-yield strike would be comparable to the human losses from conventional operations. In fact, the fallout contours that are visible in figure 3 for the low-yield scenario correspond to annual radiation levels deemed acceptable by the U.S. Occupational Safety and Health Administration.

The precise results of the HPAC simulation should be treated with skepticism: wind speed and direction change constantly, altering fallout patterns. The amount of fallout generated in the low-yield scenario is so low, however, that the results of figure 3 are robust regardless of which way the wind blows:

few people located away from the actual targets would be killed. The point of figure 3 is not to predict the outcome of a counterforce strike on North Korea, but to reveal the relationship between accuracy and fallout. When accuracy was poor, the only approach to nuclear counterforce was high-yield strikes, which would create catastrophic results such as the one depicted above. The accuracy revolution has changed the calculus, however; low-fatality nuclear strikes are now possible.[62]

The accuracy revolution is ongoing. As accuracy continues to improve, the effectiveness of conventional attacks on hard targets will continue to increase. Today, low-yield nuclear weapons can destroy targets that once required very large yield detonations. In the future, many of those targets will be vulnerable to conventional attacks.

In sum, from the start of the nuclear age to the present, force planners have relied on hardening as a key strategy for ensuring the survivability of their arsenals. That strategy made sense, and until recently ensured that disarming strikes would not only fail, but also kill millions of civilians in the process. Technology never stands still, however, and the technical foundations of deterrence, particularly for the strategy of hardening, have been greatly undermined by leaps in accuracy.

Counterforce in the Age of Transparency

While advances in accuracy are negating hardening as a strategy for protecting nuclear forces, leaps in remote sensing are undermining the other main approach: concealment. Finding concealed forces, particularly mobile ones, remains a major challenge. Trends in technology, however, are eroding the security that mobility once provided. In the ongoing competition between "hiders" and "seekers," waged by ballistic missile submarines, mobile land-based missiles, and the forces that seek to track them, the hider's job is growing more difficult than ever before.

Five trends are ushering in an age of unprecedented transparency.[63] First,

62. Countries may respond to these advances by putting some counterforce targets in urban areas, denying their adversaries the option of low-fatality nuclear strikes. Doing so, however, would exacerbate the vulnerability of those targets in other ways. For example, mobile missiles deployed in or near cities would be exposed to surveillance techniques that would be more difficult to employ if the launchers were deployed in rural areas. It is easier to surreptitiously emplace sensors and tracking systems in urban areas. Protection from low-fatality nuclear strikes would thus come at the cost of concealment, and, if target intelligence improved sufficiently, those city-based weapons would be more vulnerable to conventional strikes.

63. For an overview of modern remote sensing capabilities, see Thomas L. Lillesand, Ralph W. Kiefer, and Jonathan W. Chipman, *Remote Sensing and Image Interpretation*, 7th ed. (Hoboken, N.J.:

sensor platforms have become more diverse. The mainstays of Cold War technical intelligence—satellites, submarines, and piloted aircraft—continue to play a vital role, and they are being supplemented by new platforms. For example, remotely piloted aircraft and underwater drones now gather intelligence during peacetime and war. Autonomous sensors, hidden on the ground or tethered to the seabed, monitor adversary facilities, forces, and operations. Additionally, the past two decades have witnessed the development of a new "virtual" sensing platform: cyberspying.[64]

Second, sensors are collecting a widening array of signals for analysis using a growing list of techniques. Early Cold War strategic intelligence relied heavily on photoreconnaissance, underwater acoustics, and the collection of adversary communications—all of which remain important. Now, modern sensors gather data from across the entire electromagnetic spectrum; they employ seismic and acoustic sensors in tandem; and they emit radar at various frequencies depending on their purpose, for example, to maximize resolution or to penetrate foliage. Modern remote sensing exploits an increasing number of analytic techniques, including spectroscopy to identify the vapors leaking from faraway facilities, interferometry to discover underground structures, and signals processing techniques (such as those underpinning synthetic aperture radars) that allow radars to perform better than their antenna size would seem to permit.[65]

Third, remote sensing platforms increasingly provide persistent observation. At the beginning of the Cold War, strategic intelligence was hobbled by sensors that collected snapshots rather than streams of data. Spy planes sprinted past targets, and satellites passed overhead and then disappeared over the horizon. Over time those sensors were supplemented with platforms that remained in place and soaked up data, such as signals intelligence antennas, undersea hydrophones, and geostationary satellites. The trend toward persistence is continuing. Today, remotely piloted vehicles can loiter near enemy targets, and autonomous sensors can monitor critical road junctures for months or years. Persistent observation is essential if the goal is not merely to count enemy weapons, but also to track their movement.

Wiley, 2015). For an excellent discussion of the military implications of advanced remote sensing technology—written in the context of capabilities as they were in 2001—see Alan J. Vick et al., *Aerospace Operations against Elusive Ground Targets* (Santa Monica, Calif.: RAND Corporation, 2001).

64. See Vick et al., *Aerospace Operations against Elusive Ground Targets*, appendix A; and Gordon Corera, *Cyberspies: The Secret History of Surveillance, Hacking, and Digital Espionage* (New York: Pegasus, 2015).

65. For a discussion of some of these advances, see Defense Advanced Research Projects Agency (DARPA), *Breakthrough Technologies for National Security* (Arlington, Va.: DARPA, 2015).

The fourth factor in the ongoing remote sensing revolution is the steady improvement in sensor resolution. In every field that employs remote sensing technology, including medicine, geology, and astronomy, improved sensors and advanced data processing are permitting more accurate measures and fainter signals to be discerned from background noise. The leap in satellite image resolution is but one example: the first U.S. reconnaissance satellite (Corona) could detect objects as small as 25 feet across. Today, even commercial satellites (e.g., DigitalGlobe's WorldView-3 and WorldView-4) can collect images with 1-foot resolution, and U.S. spy satellites are reportedly capable of resolutions less than 4 inches.[66] Advances in resolution are not merely transforming optical remote sensing systems; they are extending what can be seen by infrared sensors, advanced radars, interferometers and spectrographs, and many other sensors.

The fifth key trend is the huge increase in data transmission speed. During the first decades of the Cold War, it took days or longer to transmit information from sensors to analysts. At least a full day passed before the photographs snapped by U-2 aircraft were developed and analyzed. Early satellites were slower: the satellite had to finish its roll of film, and then eject the canister, which would be caught midair and flown to a facility for development and analysis. All told, images collected at the beginning of a satellite mission might take weeks before they arrived at an analyst's desk. Today, by contrast, intelligence gathered by aircraft, satellites, and drones can be transmitted in nearly real time. The data can be transmitted to intelligence analysts, political leaders, and in some cases directly to military commanders conducting operations.

None of these technological trends alone is transformative. Taken together, however, they are creating a degree of transparency that was unimaginable even two decades ago. These new remote sensing technologies are not proliferating around the world evenly; the United States, for example, seems to have exploited new sensing technologies more intensively than other countries. Many countries are developing expertise in advanced sensing, however. The sensing revolution is a global phenomenon, with implications for the survivability of all countries' nuclear arsenals.

Remote sensing technologies have improved greatly, but the crucial question is whether these advances have meaningfully increased the vulnerability of the two most elusive types of nuclear delivery systems: SSBNs and mobile land-based missiles. If the ability to track submarines at sea or mobile missiles

66. Richard Hollingham, "Inside the Google Earth Satellite Factory," *BBC News*, http://www.bbc.com/future/story/20140211-inside-the-google-earth-sat-lab; and "WorldView-4 Launch Page" (Bethesda, Md.: Lockheed Martin, n.d.), http://www.lockheedmartin.com/worldview4.

on patrol remains out of reach, then the counterforce improvements we identify are less significant, at least for now. In fact, SSBNs have never been as invulnerable as analysts typically assume, and advances in remote sensing appear to be reducing the survivability of both submarines and mobile missiles.

REMOTE SENSING AND TRACKING SUBMARINES

During the Cold War, the competition between submariners and antisubmarine warfare operators was shrouded in secrecy, but that history is finally being revealed. We now know that the United States was able to locate, and even track, Soviet SSBNs during extended periods of the Cold War.[67]

The core of U.S. ASW efforts against the Soviet Union lay in a series of breakthroughs in passive sonar and signals processing, as well as doctrine and tactics to exploit those advances. Starting in the 1950s, the United States deployed an expanding network of underwater hydrophones designed to identify and locate adversary submarines. Data from the hydrophones were transmitted across undersea cables to onshore computing facilities, where powerful computers discerned the faint sounds of submarines from ocean noise. Potential targets were then passed along to aircraft and attack submarines (SSNs) for further location and tracking. U.S. capabilities to track Soviet submarines leapt forward in the late 1960s and 1970s, as the United States deployed new attack submarines, which were equipped with powerful sonars in their bows, towed sonar arrays, and improved on-ship computing power, giving U.S. SSNs an unprecedented combination of acoustic gathering and data processing capabilities.[68]

The competition between Soviet SSBNs and the pack of U.S. submarines, aircraft, and surface ships hunting them varied throughout the Cold War. There were periods in which U.S. forces were winning, trailing every Soviet SSBN on patrol, from port to sea and back. In later periods, after discovering their vulnerability, the Russians pulled their forces into protected "bastions" near Soviet territory to counter the U.S. ASW strategy. The United States did not give up, and worked until the end of the Cold War (and beyond) to regain undersea superiority.

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67. Among journalistic accounts, which are based on interviews with ASW operators, see Sasgen, *Stalking the Red Bear*; and Sherry Sontag and Christopher Drew, with Annette Lawrence Drew, *Blind Man's Bluff: The Untold Story of American Submarine Espionage* (New York: PublicAffairs, 1998). For academic analyses, see Coté, *The Third Battle*; Long and Green, "Stalking the Secure Second Strike"; and Brendan Rittenhouse Green and Austin Long, "The Role of Clandestine Capabilities in World Politics," paper presented at the annual meeting of the American Political Science Association, Philadelphia, Pennsylvania, September 1–4, 2016.

68. Coté, *The Third Battle*; Long and Green, "Stalking the Secure Second Strike"; and Green and Long, "The Role of Clandestine Capabilities in World Politics."

The duration of U.S. Cold War ASW superiority cannot be accurately assessed today because of enduring classification constraints. But for periods of the superpower competition, U.S. naval leaders believed they had the ASW problem well in hand. As the former commander of the U.S. Pacific Fleet in the mid-1980s remarked, the United States was able to "identify by hull number the identity of Soviet subs . . . and know exactly where they were. In port or at sea. If they were at sea, N3 [director for operations] had an SSN [on them]."[69]

There are three key lessons to draw from the Cold War ASW competition. First, previous advances in remote sensing greatly increased the vulnerability of deployed submarines.[70] Second, escaping vulnerability was no easy task. In the late 1960s, the Soviet Union learned that its submarines were vulnerable. But despite Moscow's significant economic and technological resources, it took the Soviet navy more than a decade to develop good countermeasures against the evolving U.S. ASW capabilities.[71]

Third, and most broadly, the Cold War ASW competition demonstrates that the deployment of ballistic missile submarines neither ended the Cold War nuclear competition nor negated hopes on either side of attaining military superiority. The United States led the undersea competition for a time because of its superior technology and tactics; the Soviet Union developed countermeasures because it discovered its vulnerabilities and innovated. This back-and-forth struggle between hiders and seekers looks more like a traditional struggle for naval superiority than the common depiction of invulnerable submarines.

Today's technological advances in remote sensing, data processing, and communication are occurring at a rapid pace, and their ultimate impact on the submarine competition is too uncertain to predict with confidence (especially given the tight controls over information on contemporary ASW capabilities). Yet, there are good reasons to suspect that the dramatic leaps in remote sensing are increasing the transparency of the seas and undermining the ability of submarines to remain concealed.[72] Some of the promising new anti-submarine

69. As quoted in Long and Green, "Stalking the Secure Second Strike," p. 51.
70. Although U.S. Cold War ASW successes rested heavily on technical breakthroughs in acoustics and data processing, well-trained operators and intelligence analysts were essential to the success.
71. The main Soviet countermeasures included deploying longer-range SLBMs, which permitted Soviet submarines to target the U.S. homeland from well-defended bastions near the Soviet coast, and developing quieter Soviet SSBNs and SSNs to elude detection and threaten the submarine hunters. It appears that Soviet countermeasures significantly reduced the U.S. undersea advantage, but this judgment (like the Cold War assumptions that the United States was not tracking Soviet SSBNs) is tentative given that relevant documents remain classified.
72. See Bryan Clark, *The Emerging Era in Undersea Warfare* (Washington, D.C.: Center for Strategic and Budgetary Affairs, 2015); James Holmes, "Sea Changes: The Future of Nuclear Deterrence," *Bulletin of the Atomic Scientists*, Vol. 72, No. 4 (July 2016), pp. 228–233; and Bryan Clark, "Undersea

technologies include improved acoustic sensors (including low-frequency active sonars and new networks of seabed passive sonars); non-acoustic techniques (such as laser detection); sophisticated "big data" analysis (which exploits leaps in processor speed to sift vast quantities of sensor data); and a variety of unmanned and autonomous undersea vehicles (including those designed to find and shadow adversary submarines for weeks or months).[73]

The point is not that submarines are now easy to locate or that the challenges of ASW have been solved. Locating technologically sophisticated, well-operated submarines in vast ocean sanctuaries remains a substantial challenge. Rather, the key point is that even the nuclear delivery system sometimes touted as the most survivable has been vulnerable in the past and appears to be increasingly vulnerable today, as ASW efforts and capabilities rapidly improve.

What about mobile land-based missiles? Are breakthroughs in sensing technology increasing their vulnerability as well?

REMOTE SENSING AND HUNTING MOBILE MISSILES

We illustrate the impact of two advanced surveillance systems, radar satellites and remotely piloted aircraft, on the survivability of mobile land-based nuclear missiles. The effectiveness of sensing systems depends on the characteristics of the target country—for example, its size, location, topography, and defenses. As such, their impact is difficult to quantify in the abstract. Instead, we explore the potential contributions of two advanced sensor systems in a hypothetical case: a U.S.-led operation to destroy a small arsenal of North Korean nuclear-tipped mobile missiles.[74] We assume that North Korea's TELs are postured like most other countries' mobile missiles; they remain in hardened shelters during peacetime, with plans to disperse a portion of the force during a conflict.[75]

U.S. and allied strategic intelligence would have at least three critical roles in

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Cables and the Future of Submarine Competition," *Bulletin of the Atomic Scientists*, Vol. 72, No. 4 (July 2016), pp. 234–237.

73. Clark, *The Emerging Era in Undersea Warfare*, pp. 8–17; Holmes, "Sea Changes," pp. 229–230; and Clark, "Undersea Cables and the Future of Submarine Competition," pp. 235–237.

74. This scenario is salient because if conventional war erupts on the Korean Peninsula, the United States and South Korea may feel compelled to destroy North Korea's nuclear capabilities. See Lieber and Press, "Coercive Nuclear Campaigns in the 21st Century"; Lieber and Press, "The Next Korean War"; and Talmadge, "Would China Go Nuclear?"

75. Unlike the Soviet Union, which conducted armed peacetime deterrent patrols, most countries with nuclear-armed mobile forces appear to keep their TELs in hardened facilities during peacetime (and even during crises). On China's doctrine, see Li, "Tracking Chinese Strategic Mobile Missiles," pp. 7–11; and Wu, "Certainty of Uncertainty," pp. 586–587. On Israeli basing, see "Beit Zachariah/Zekharyeh," *Globalsecurity.org*, n.d., http://www.globalsecurity.org/wmd/world/israel/sedot_mikha.htm.

support of a military operation against North Korean TELs. The first, a peacetime mission called "intelligence preparation of the battlefield" (IPB), involves locating North Korea's nuclear and missile facilities, identifying the patrol routes utilized by its missile forces, learning its organizational routines, and mapping its command and communication network. The other two roles are principally wartime missions. "Detection" refers to sensing possible targets; it typically involves sensors that can monitor large areas, but that have inadequate resolution for positive identification or targeting. "Identification" is the next step; once a possible target is detected, other platforms (often with higher-resolution sensors) are cued to identify and precisely locate the target.[76]

SATELLITES/SAR SENSORS. A core element of U.S. surveillance capabilities lies in a constellation of satellites that use synthetic aperture radar to image targets on the ground. Satellites provide a unique capability to peer deep into adversary territory, and they are especially useful for missions that require frequent observations of critical facilities. Whereas manned aircraft and unmanned aerial vehicles (UAVs) are often restricted from adversary airspace, satellites routinely overfly adversary territory. Moreover, unlike satellites with optical or infrared sensors, radar satellites can image targets at night and through cloudy weather.

Until recently, the type of radar employed on most satellites—synthetic aperture radar (SAR)—could not image moving targets, limiting the effectiveness of space-based sensors for hunting mobile missiles.[77] But over the past two decades, engineers have developed data-processing techniques that enable SAR systems to detect moving targets and determine their speed and direction of travel.[78] Although the precise capabilities of intelligence satellites are class-

76. The IPB framework for elusive targets is reflected in Vick et al., *Aerospace Operations against Elusive Ground Targets*, especially chap. 4 and appendix B. Some sensing platforms carry sensors for both detection and identification. For example, the RQ-4 Global Hawk drone has a ground moving target indicator (GMTI) radar that can scan a wide area and then switch to "spot" mode to look more closely at an identified target.

77. For natural aperture radars, image resolution is constrained by the size of the antenna, and operating very large antennas in space is currently impractical. As a result, satellites employ synthetic aperture radars, which use the movement of the satellite to simulate the function of a larger antenna, allowing satellites to generate images at higher resolution than their antenna size would normally permit. Until recently, however, SAR systems could not image moving targets. See Joseph Post and Michael Bennett, "Alternatives for Military Space Radar" (Washington, D.C.: Congressional Budget Office, January 2007).

78. For one of the earliest papers on using SAR for tracking mobile targets, see R.P. Perry, R.C. DiPietro, and R.L. Fante, "SAR Imaging of Moving Targets," *IIEEE Transactions on Aerospace and Electronic Systems*, Vol. 35, No. 1 (January 1999), pp. 188–200. For a recent study that employs a civilian radar satellite to identify the location and velocity of cars and trucks, see Christoph H. Gierull, Ishuwa Sikaneta, and Delphine Cerutti-Maori, "Two-Step Detector for RADARSAT-2's Experimental GMTI Mode," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 51, No. 1 (January 2013), pp. 436–454.

ified, civilian radar satellites can scan approximately 150-kilometer-wide swaths along the ground as they pass overhead with sufficient resolution to detect truck-sized moving vehicles.[79] New techniques are being developed that may soon double or triple the width of the swath that can be scanned on each pass.[80]

SAR-equipped satellites, now able to find mobile targets, have the potential to transform counter-TEL operations. If U.S. intelligence satellites can detect moving vehicles within a 150-kilometer-wide swath along the ground, a conservative assumption given that a civilian satellite launched nearly a decade ago can do so, then centering the radar on a mobile missile garrison would put all the roads within two hours' drive-time of that facility within the radar's swath width.[81] A single satellite can generate up to twelve 150 kilometer x 150 kilometer swaths in a single pass over North Korea, enough to image all the country's roads more than once—and key sections multiple times—before passing over the horizon.[82]

Although SAR satellites have become powerful tools for hunting TELs, they have important limitations. Surveillance satellites provide only intermittent coverage of key areas, passing overhead and then descending over the horizon. Thus, even if a constellation of satellites could image the entire road network in North Korea every hour, North Korean TELs might be able to disperse without being observed, by seeking shelter whenever a satellite approaches. Furthermore, if many of North Korea's critical facilities are located in its mountainous regions, topography may block the satellite's line-of-sight, which would allow targets within the swath to be hidden from the radar. The potential effectiveness of radar satellites for hunting mobile missiles, therefore, de-

79. One 2015 study used RADARSAT-2 data to scour 150-kilometer-wide swaths of sea, locating and characterizing the velocity of moving vessels. See Louis-Philippe Rousseau, Christoph Gierull, and Jean-Yves Chouinard, "First Results from an Experimental ScanSAR-GMTI Mode on RADARSAT-2," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, Vol. 8, No. 11 (November 2015), pp. 1–13. One of the authors of that paper confirmed via personal communication that the technique that the authors employed and the large swath widths that they used should be applicable to truck-sized vehicles on the ground.

80. Using the experimental "High-Resolution-Wide-Swath" mode, SAR satellites may be able to generate 300 to 500–kilometer-wide swaths with sufficient resolution to track truck-sized moving targets. See Stefan V. Baumgartner and Gerhard Krieger, "Simultaneous High-Resolution Wide-Swath SAR Imaging and Ground Moving Target Indication: Processing Approaches and System Concepts," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, Vol. 8, No. 11 (November 2015), pp. 1–15.

81. With a 150-kilometer-wide swath, the terrain within 75 kilometers of either side of the garrison would be within the zone covered by the radar. A typical TEL can move approximately 40 kilometers per hour. Given that roads in North Korea are not perfectly straight, the actual driving time to escape a 75-kilometer-wide swath (on either side of the garrison) would be at least two hours.

82. See the online appendix.

pends on two key factors: the time interval between satellite passes and the percentage of road network that is observable in a given pass.[83]

To assess the effectiveness of SAR satellites for hunting North Korean mobile missiles, we conducted an analysis with three key steps. First, we created a digital map of North Korea's roads. Second, we used geospatial analysis software to determine the visible portion of those roads as a function of a satellite's position. Third, we calculated the frequency with which satellites pass within an orbital band that provides high levels of visibility of the road network.[84]

Our analysis of satellite orbits and North Korean topography reveals that satellites passing through an orbital band that stretches as far as 1,500-kilometer lateral distance from the Korean Peninsula can view, on average, 90 percent of North Korean roads. A typical radar satellite (which operates in low earth orbit) will pass through such a band, what we call a "usable pass," roughly 2.5 times per day. The total number of usable passes per day thus depends on the number of SAR satellites in orbit that are available for hunting mobile missiles. The number of available satellites, in turn, depends on the willingness of the United States and its close allies to share sensitive satellite imagery, the technical preparations that have been undertaken to facilitate that sharing, and the precise technical capabilities of the satellites.

Table 2 shows the implications of different assumptions about those uncertainties. If the United States and key allies create the political and technical arrangements to share satellite data during wartime, North Korean TEL commanders would have little time between passes—specifically, as few as 24 minutes.[85]

Twenty-four minutes between satellite passes could provide enough time for TELs or other vehicles to move quickly from shelter to shelter, but that strategy requires precise information on satellite orbits, and the short time interval between passes leaves little margin for error for vehicles racing for cover. Moreover, the challenge for TEL operators is more serious than the data suggest. The analysis here focuses on the twenty military and intelligence SAR

83. These two factors are linked. If North Korea's topography is sufficiently problematic that only satellites in a narrow orbital band (i.e., almost directly overhead) can see over the mountains, then there will be fewer usable passes each day (and hence a longer interval between passes). On the other hand, if even satellite passes that are far from North Korea can see the roads, then there will be many usable passes per day.

84. See the online appendix for details on all three steps in the analysis.

85. The United States may or may not have agreements and technology in place to rapidly share sensitive satellite imagery, even with its closest military partners. From the perspective of North Korean missile commanders, however, a German or Japanese SAR satellite pass overhead poses a major threat.

Table 2. Synthetic Aperture Radar (SAR) Satellites and Frequency of Usable Passes

		Cumulative		
	Number of SAR Satellites	Available Satellites	Usable Passes per Day	Minutes between Passes
United States	6	6	15	91
Other NATO	9	15	37	34
Japan	3	18	44	27
Israel	2	20	50	24

NOTE: The category "Number of SAR Satellites" counts major military and intelligence SAR satellites operated by the United States and key allies. The other columns are cumulative and show how satellite coverage grows when one adds the assets of various U.S. partners. "Usable Passes per Day" indicates the daily satellite overflights that pass through an orbital band that offers, on average, 90 percent coverage of North Korean roads.

satellites, not the half dozen or more U.S. and allied civilian platforms that might be pressed into service in wartime.[86] Nor does the analysis count the optical and infrared satellites that supplement SAR coverage. Finally, the number and capability of radar satellites available to the United States is growing.[87] As that number increases, the window for mobile missiles to scoot away without being observed will narrow further.

SAR satellites do not solve the problem of locating mobile targets. For one thing, Russia and China are improving their ASAT capabilities, partly in response to U.S. capabilities.[88] Furthermore, adversaries will seek to place missile garrisons and conduct deterrent patrols in locations that are difficult to observe.[89] Those choices, however, force adversaries into ever-narrower zones, which then become the focus of other surveillance tools—for example, stealthy penetrating UAVs and unattended ground sensors.

86. The major military and intelligence radar satellites operated by the United States and key allies include Lacrosse 3–5 and Topaz 1–3 (United States); SAR-Lupe 1–5 (Germany); COSMO A–D (Italy); IGS 7a, IGS 8a, and a third satellite with name unclear (Japan); and OFEQ 8 and OFEQ 10 (Israel). Civilian radar satellites operated by allied countries include TerraSAR-X and TanDEM-X (Germany); Copernicus Sentinal-1 and -3 (European Union); KOMPSat-5 (South Korea); ALOS-2 (Japan); PAZ (Spain); and RADARSAT-2 (Canada). See "Synthetic Aperture Radar (SAR) Satellites" (Boulder, Colo.: UNAVCO, August 7, 2015), https://www.unavco.org/instrumentation/geophysical/imaging/sar-satellites/sar-satellites.html.

87. Although some older satellites on our list may have limited capabilities for this mission (e.g., they may have single-channel receivers), new satellites currently being deployed may supplement those capabilities (e.g., small cube satellites may orbit near an older radar satellite and serve as a second receiver). Most important, as the number of radar satellites continues to grow, U.S. and allied capabilities will exceed those described in table 2.

88. See Eric Heginbotham et al., *The U.S.-China Military Scorecard: Forces, Geography, and the Evolving Balance of Power, 1996–2017* (Santa Monica, Calif.: RAND Corporation, 2015), chap. 10. Of course, the United States is seeking to counter anti-satellite weapon technologies.

89. Li, "Tracking Chinese Strategic Mobile Missiles," pp. 7–11, 15–25.

In terms of the three key sensing missions (IPB, detection, and identification), SAR-equipped satellites offer a high level of capability for the IPB mission, because they can repeatedly image stationary or moving targets in peacetime. They also contribute a high level of capability to detection, by offering frequent wide-area coverage of North Korean roads. Finally, SAR satellites offer fairly good capability for the identification mission: they can produce high-resolution images of stationary TELs and enough resolution of moving vehicles to determine that a target is "truck-sized."[90]

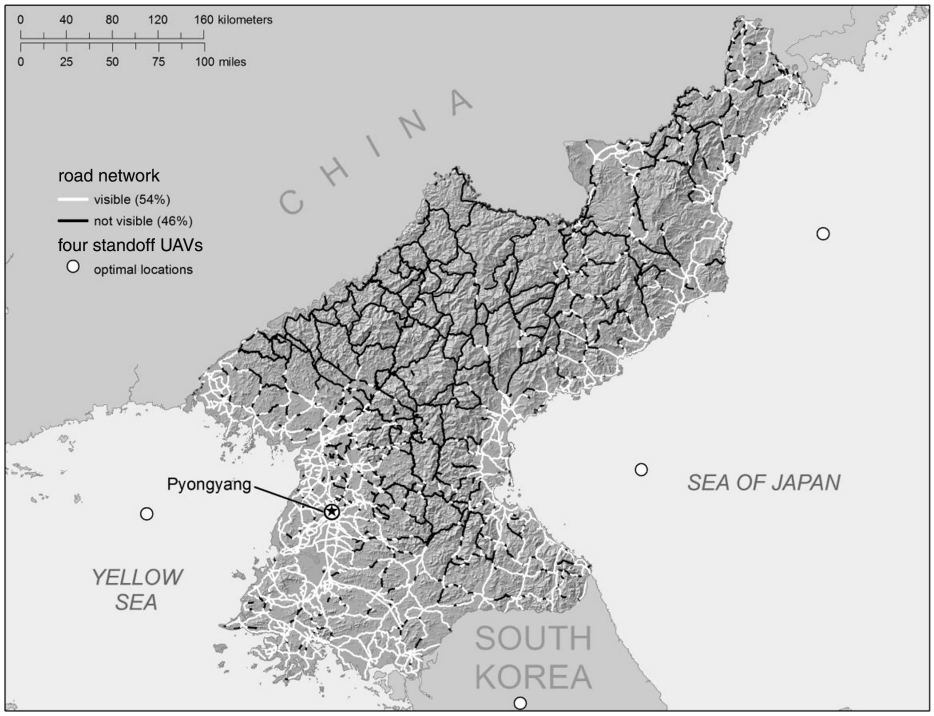
UAVs/SAR sensors. A second set of sensing capabilities lies in a fleet of aircraft, including manned and remotely piloted vehicles, that use powerful radars to scan adversary territory. These aircraft carry SARs, and many are equipped with Ground Moving Target Indicator (GMTI) radars, allowing them to create high-resolution images of stationary targets or track a large number of moving vehicles. Most surveillance aircraft must operate from "standoff" distances to reduce their vulnerability to air defenses. Some drones, however, are stealthy and can penetrate adversary airspace. Below we illustrate the capabilities of standoff SAR/GMTI platforms and penetrating UAVs in the context of a U.S. and allied operation against North Korean mobile missiles.

The United States uses several types of aircraft for standoff radar-reconnaissance missions; we base our model on one of them: the remotely piloted RQ-4 Global Hawk. We explore the potential effectiveness of radar surveillance from four continuous orbits 80 kilometers outside North Korean territory.[91] ArcGIS software allows us to identify orbital locations that maximize coverage of North Korean roads, as well as calculate the visible percentage of the road network from those locations.[92] Figure 4 shows the results.

Figure 4 reveals that even against a small country such as North Korea, standoff airborne radars cannot, by themselves, provide complete coverage of key roads and regions. Four orbits can observe 54 percent of North Korea's roads; the remainder is out of sensor range or shielded by mountainous terrain. These results also suggest, however, that standoff UAVs could play a crucial role in a sensing operation; that is, the ability to continuously monitor

90. Identifying a vehicle as truck-sized might be sufficient for a strike, depending on the context of the conflict. If, during a war, North Korea has employed nuclear weapons, detecting a large vehicle on a road near a North Korean missile garrison may be enough to trigger a strike against the vehicle. The level of identification required to trigger a strike presumably depends on the weapons available to the United States for the strike: the threshold for launching a conventional weapon at a suspected TEL is presumably lower than the threshold for employing nuclear weapons.
91. A standoff distance of 80 kilometers puts the aircraft outside the range of most North Korean air defenses. We assume a sensor range of 240 kilometers, which was the reported GMTI range of joint surveillance target attack radars during the 1991 Persian Gulf War. Our results are not sensitive to sensor-range assumptions because even at 200 kilometers, the beam is grazing the ground at a shallow angle, allowing the mountainous topography to constrain line of sight.
92. See the online appendix for calculations.

Figure 4. Coverage of North Korea with Standoff Unmanned Aerial Vehicles (UAVs)



NOTE: The white circles depict potential orbital locations for four UAVs; the locations were selected to maximize surveillance of North Korea's road network. The orbits are located 80 kilometers from North Korea's territory at an altitude of 60,000 feet, which reflect plausible operations for RQ-4 Global Hawks. White road segments are observable from at least one of the locations. For additional discussion of the underlying analysis, see the online appendix at http://dx.doi:10.7910/DVN/NKZJVT. The image was created using ArcGIS and road data from OpenStreetMap and DIVA-GIS.

roughly half of North Korea's road network during a conflict would compel North Korea to constrain its mobile missile operations to the north-central region of the peninsula.

In addition to standoff UAVs, the United States has developed drones for so-called penetrating operations.[93] These UAVs reduce their visibility to enemy ra-

93. Two such stealthy drones are the RQ-170 and RQ-180. See Amy Butler and Bill Sweetman, "Secret New UAS Shows Stealth, Efficiency Advances," *Aviation Week*, December 6, 2013, http://aviationweek.com/defense/secret-new-uas-shows-stealth-efficiency-advances; and John A. Tirpak, "For Those Hard-to-Reach Areas," *Air Force Magazine*, June 10, 2014, http://www.airforcemag.com/DRArchive/Pages/2014/June%202014/June%2010%202014/For-Those-Hard-to-Reach-Areas.aspx.

dar by utilizing stealth technologies and a combination of passive sensors and "low-probability of intercept" (LPI) radars to observe targets on the ground.[94]

Even sophisticated, stealthy UAVs are vulnerable to air defenses. To some extent their vulnerability depends on technical questions, for example, the state of competition between radar engineers and designers of stealth technology. The vulnerability of penetrating drones, however, depends greatly on their mission. Of the two critical wartime missions, "detection" is likely more dangerous than "identification." The detection mission—continuously monitoring a large area to detect possible targets—would require a drone to remain within the line-of-sight of a large portion of adversary territory. The mission would, therefore, require the drone to fly at high altitude (to maximize line-of-sight) and possibly use active sensors (to maximize the drone's sensor range). The identification mission, on the other hand, would allow penetrating drones to protect themselves better: to operate at lower altitude so that terrain would shield them from enemy sensors, and fly (when cued by detection systems) to investigate a possible TEL. Only then would the penetrating UAV employ LPI or passive sensors to examine the potential target.

We used ArcGIS to explore the potential capability of penetrating drones in the identification mission by determining the percentage of the North Korean road network that would be visible using four UAV orbits. Because the penetrating UAVs would need to rapidly identify the vehicles detected by other sensors, we restricted the UAVs to 5 minutes of flight time to maneuver into position to observe the suspected TEL.[95] Furthermore, because LPI radars and passive sensors have shorter range than the powerful radars on standoff platforms, we limit the sensor range to 50 kilometers.[96]

Our analysis reveals that four penetrating drones, operating as we describe above, can identify targets along 84 percent of North Korea's roads.[97] As fig-

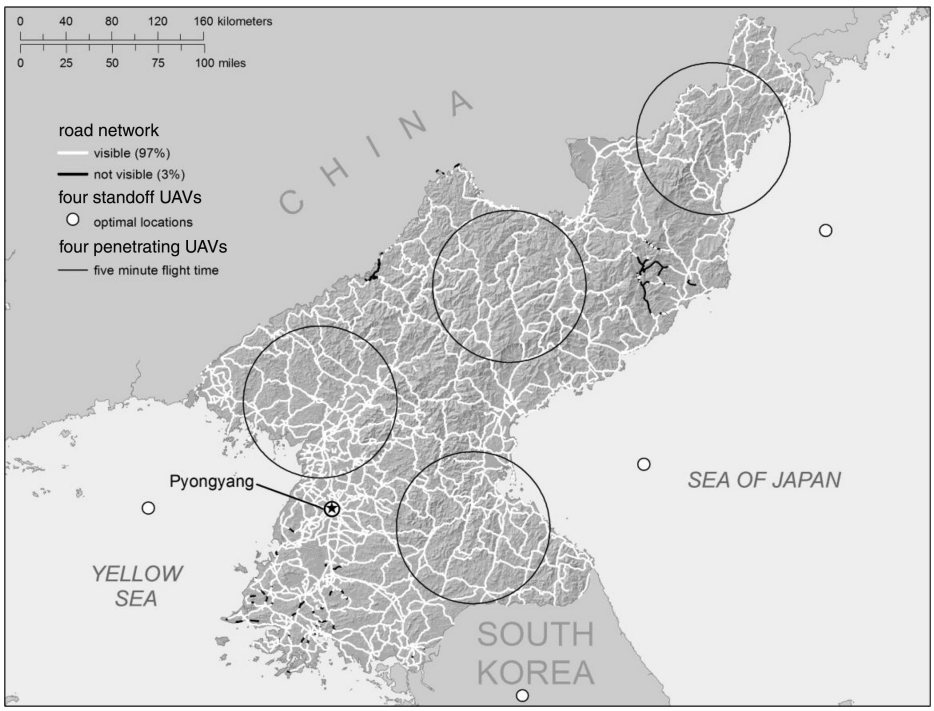
94. Passive sensors "look" but do not emit. Active sensors (those that emit) generally have longer range, but increase the risk that the UAV will be detected. LPI radars emit but are designed to hinder adversary efforts to detect and locate the emitter.

95. RQ-170s (and probably RQ-180s) are equipped with turbofan engines, implying a flight speed of approximately 800 kilometers per hour. We assume that once cued to identify a target, the UAVs gain altitude, if necessary, to attain line-of-sight to the target.

96. In the 5 minutes we allow the UAVs to maneuver, they can fly approximately 67 kilometers given 800 kilometer per hour flight speed. Some sources suggest that the Lynx Multi-mode Radar, currently deployed on some UAVs, can sense a TEL-sized target moving at 11 kilometers per hour out to 25 kilometers. See Sherrill Lingel et al., "Methodologies for Analyzing Remotely Piloted Aircraft in Future Roles and Missions" (Santa Monica, Calif.: RAND Corporation, 2012), p. 73. (A TEL moving more quickly would be observable at a longer range.) Our results are not sensitive to modest deviations in sensor range. If the sensor range on U.S. penetrating UAVs were 25 percent less than we estimate (35 kilometers instead of 50 kilometers), one additional minute of flight time would compensate. See ibid., pp. 25–27, 73–74.

97. Maintaining four continuous orbits during a conflict would likely require at least 12 UAVs—not accounting for losses from air defenses.

Figure 5. Coverage of N. Korea with Standoff and Penetrating Unmanned Aerial Vehicles



NOTE: The white circles depict potential orbital locations for four UAVs operating 80 kilometers outside North Korea's territory. The black circles depict the area over North Korea that four penetrating UAVs can overfly within five minutes of flight time starting from the center of each circle. Road segments are coded as visible (white) if they are observable from either a standoff or penetrating UAV. For discussion of the underlying analysis, see the online appendix at http://dx.doi:10.7910/DVN/NKZJVT. The image was created using ArcGIS and road data from OpenStreetMap and DIVA-GIS.

ure 5 shows, penetrating and standoff systems would be particularly effective in combination, increasing the road network coverage to 97 percent. Assuming that penetrating UAVs can be cued by other reconnaissance systems, such as satellites, unattended ground sensors, or (near the coast) standoff drones, North Korean TEL operators would have great difficulty moving safely along the country's road network without being detected. If U.S. and South Korean intelligence had identified mobile missile garrisons and operating areas before the conflict, the regions surrounding those zones might be fully covered by only one or two drone orbits.[98]

98. The results in the North Korea scenario should not be applied directly to other potential U.S. adversaries—such as China or Russia—because those countries are larger, with different topogra-

Each of the sensing systems explored here has important limitations. For example, radar satellites provide wide-area coverage, but do so intermittently and at only moderate resolution. Standoff drones provide persistent coverage, but only near the coast. Penetrating drones can provide persistent coverage inland (at the cost of increased risk to the aircraft) or intermittent inland coverage at lower risk. In many cases, however, the capabilities of one system can offset the limits of another. Moreover, this analysis merely scratches the surface in terms of new sensing platforms (e.g., unattended ground and seabed systems), signals (e.g., high-resolution spectroscopy), and approaches (e.g., cyber intrusions), many of which would be employed together for the same mission.

Old assumptions about the survivability of mobile forces need to be revised in light of new sensing technologies and capabilities. Concealment is not impossible, of course. An adversary's mobile delivery systems can remain secure if its air defenses can keep UAVs at bay, its navy can keep enemy ASW forces from its coastal waters, and anti-satellite technology can blind satellites. But in this new era of transparency, whether concealed forces are survivable or not depends on the state of competition between opposing intelligence and military organizations. Survivability through concealment can no longer be assumed.

What About Countermeasures?

Countries will surely address the growing vulnerability of their nuclear arsenals by trying to develop countermeasures to thwart advanced sensor and strike systems. They will seek to deploy radar jammers, anti-satellite weapons, and decoys. They will try to adapt mobile missile doctrines to reduce vulnerability, for example, by timing movements to elude satellites and minimizing communications to thwart signals intelligence efforts. The new era of counterforce will not be static; it will be characterized by vigorous efforts to develop countermeasures, as well as equally vigorous efforts to overcome them.

Yet, there are good reasons to expect that the net result of these efforts will leave nuclear delivery systems more vulnerable than they have been in the recent past. First, hunters are poised to do well in the back-and-forth battle of countermeasures. Counterforce is the domain of the powerful; those that are seeking to track enemy nuclear forces typically have greater resources than their rivals.[99] Additionally, the countries that are leaders in sensing technology

phy, bigger arsenals, and more modern defenses. The sensor revolution is significantly increasing the vulnerability of the Chinese and Russian arsenals as well, but not as quickly as it is undermining North Korea's force.

99. Nuclear weapon states that are weaker than their main rivals typically strive to develop survivable nuclear forces in order to stalemate more powerful foes. Counterforce tends to be the do-

have an advantage in the race to build (and thwart) countermeasures. As Brendan Green and Austin Long observe about the Cold War ASW competition, U.S. superiority in passive acoustics helped the United States quiet its own SSBNs, which in turn allowed it to practice and hone its tracking capabilities.[100] Expertise in sensors and countermeasures go hand in hand. Perhaps most importantly, many countermeasures reduce one vulnerability at the cost of exacerbating others. For example, limiting communications between mobile missiles or submarines and their command authorities reduces vulnerability to signals intercepts, but it increases vulnerability to attacks designed to sever (or simulate) their command and control.[101] Avoiding coastal roads neutralizes offshore sensors, but it channels forces into a smaller zone, easing the search problem. Even the simplest countermeasures, such as increasing security near sensitive facilities to prevent the emplacement of unattended ground sensors or improving air defenses around key sites to thwart UAVs, may cue hunters to the presence of high-value sites.

Second, the potential targets of disarming strikes cannot merely respond to a single counterforce technology; they must respond to a daunting list of them. The revolutions in accuracy and sensing have had multiple, synergistic effects in bolstering counterforce. The task for hiders is not simply to thwart a single platform, such as SAR satellites, but rather to develop countermeasures to the entire array of (known) capabilities deployed by the hunters. For example, North Korea may find ways to interfere with U.S. radar satellites, but that still leaves its missiles vulnerable to detection by optical satellites; UAVs; unattended ground sensors; and a variety of tagging, tracking, and locating capabilities.

Third, some vulnerabilities are difficult to fix. In the late 1960s, the Soviet Union learned that its SSBNs were being tracked by the United States, but it took more than a decade to counter this U.S. capability. Consider the challenge faced by China today in building a survivable ballistic missile submarine force; China deployed its first submarines in the 1960s, but more than half a century later Chinese submarines are still so noisy that experts predict it will be decades before Beijing can field survivable submarines.[102]

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main of the strong, which have the resources to pursue it and the incentive to negate the stalemating forces of their weaker enemies.

100. Green and Long, "The Role of Clandestine Capabilities in World Politics."

101. The United States had Cold War programs to jam and simulate communications linking Soviet nuclear command and control with deployed forces. See Benjamin B. Fischer, "CANOPY WING: The U.S. War Plan That Gave the East Germans Goose Bumps," *International Journal of Intelligence and Counterintelligence*, Vol. 27, No. 3 (2014), pp. 431–464.

102. See Wu Riqiang, "Survivability of China's Sea-Based Nuclear Forces," *Science & Global Security*, Vol. 19, No. 2 (2011), pp. 91–120; and comments by Chinese analysts in "Why Is China Modernizing Its Nuclear Arsenal?" transcript, Carnegie International Nuclear Policy Con-

The battle between countermeasures and corresponding attempts to defeat them is under way, and its outcome will likely depend on the strategic context. Rich countries with advanced research and development infrastructure are developing technology and doctrine to protect their nuclear forces in the face of improvements in weapons accuracy and remote sensing. Weaker countries with modest resources, however, will be hard pressed to develop effective countermeasures to the full spectrum of emerging means of counterforce.

Conclusion

For most of the nuclear age, there were many impediments to effective counterforce. Weapons were too inaccurate to reliably destroy hardened targets; fratricide prevented many-on-one targeting; the number of targets to strike was huge; target intelligence was poor; conventional weapons were of limited use; and any attempt at disarming an adversary would be expected to kill vast numbers of people. Today, in stark contrast, highly accurate weapons aim at shrinking enemy target sets. The fratricide problem has been swept away. Conventional weapons can destroy most types of counterforce targets, and low-fatality nuclear strikes can be employed against others. Target intelligence, especially against mobile targets, remains the biggest obstacle to effective counterforce, but the technological changes under way in that domain are revolutionary. Of the two key strategies that countries have employed since the start of the nuclear age to keep their arsenals safe, hardening has been negated, and concealment is under great duress.

The new era of counterforce helps solve one of the enduring theoretical puzzles of the nuclear age. For decades, scholars of the theory of the nuclear revolution wondered why leaders seemed to be ignoring the profound implications of nuclear weapons for international politics. In theory, nuclear weapons make states that possess them so secure that they need not engage in traditional forms of competition with adversaries, such as arms racing, alliance building, relative gains competition, and rivalry over strategic territory. In practice, all those behaviors have endured. Scholars blame the persistent discrepancy between theory and practice on misperception, illogic, or other decisionmaking pathologies. The new era of counterforce suggests, however, that leaders have been correct to perceive that stalemate can be broken, and that the nuclear balance can vary dramatically across cases. If today's secure arsenal can become tomorrow's first-strike target, then there is little reason to expect

ference, March 24, 2015, http://carnegieendowment.org/files/12-chinanucleararsenal240315wintro-formatted.pdf.

the geopolitical competition between countries to end with the deployment of seemingly secure nuclear weapons.

The policy implications of the new era of counterforce are also important. First, if nuclear forces are becoming increasingly vulnerable to counterforce, then states need to improve their retaliatory arsenals just to maintain the same level of deterrence. Given that nuclear delivery systems are expensive and must last for decades, the challenge for force planners is extraordinary: deploy weapon systems that will remain survivable for multiple generations, even as technology improves at an ever-increasing pace. Second, the growing threat to nuclear arsenals (from nuclear strikes, conventional attacks, missile defenses, ASW, and cyber operations) raises major questions about the wisdom of cutting the size of nuclear arsenals. In the past, many arms control advocates believed that arms cuts reduced the incentives for disarming strikes; whether right or wrong in the past, that assumption is increasingly dubious as a recipe for deterrence stability today.

Finally, leaps in accuracy and remote sensing should reopen debates in the United States about the wisdom of pursuing effective counterforce systems. Fielding those capabilities—nuclear, conventional, and other—may prove invaluable: enhancing deterrence during conventional wars and, if deterrence fails, allowing the United States to defend itself and its allies. Enhancing counterforce capabilities, however, may trigger arms races and other dynamics that exacerbate political and military conditions. In the past, technological conditions bolstered those who favored restraint: disarming strikes seemed impossible, so enhancing counterforce would likely trigger arms racing without much strategic benefit. Today, technological trends appear to validate the advocates of counterforce: remote sensing, conventional strike capabilities, ASW, and cyberattack techniques will continue to improve and increasingly threaten strategic forces whether or not the United States seeks to maximize its counterforce capabilities. In this new era of counterforce, technological arms racing seems inevitable, so exercising restraint may limit options without yielding much benefit.

Nuclear deterrence can be robust, but nothing about it is automatic or everlasting. Nuclear stalemate might endure among some pairs of states, and technology could someday reestablish the ease of deploying survivable arsenals. Today, however, survivability is eroding, and it will continue to do so in the foreseeable future. Weapons will grow even more accurate. Sensors will improve. The new era of counterforce will likely yield benefits to those countries that best adapt to the new landscape, and costs to those that fall behind. The first step in understanding these dynamics is to recognize the new strategic reality confronting nuclear powers today.