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Will the Drone Always Get Through? Offensive Myths and Defensive Realities

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ABSTRACT

Do emerging and disruptive technologies yield an offensive advantage? This is a question of central theoretical and substantive relevance. For the most part, however, the literature on this topic has not investigated empirically whether such technologies make attacking easier than defending, but it has largely assumed that they do. At the same time, work on the offense–defense balance has primarily focused on land conflicts, thus offering little understanding of the effect of technological change in other domains, such as the air and sea. In this article we address these gaps by investigating whether current- and next-generation drones shift the offense–defense balance toward the offense or toward offense dominance, as many assume—that is, whether drone technology can or will defeat current- and next-generation air defense systems. To answer these questions, we have explored the literature in radar engineering, electromagnetism, signal processing, and air defense operation. Our analysis challenges the existing consensus about the present and raises questions about the future. Our findings also demonstrate how important it is for the field of security studies to embrace greater interdisciplinarity in order to explore pressing policy and theoretical questions.

Do emerging and disruptive technologies yield an offensive advantage? In other words, do they make attacking easier than defending? These are pressing policy and theoretical questions whose answers have deep and far-reaching implications. Technological change that favors the offense exacerbates the security dilemma, promotes arms races, increases incentives for the employment of force, rewards first movers in a conflict, and ultimately can spiral into aggression and war.[1] This is why scholars and practitioners

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[1] Robert Jervis, "Cooperation under the Security Dilemma," *World Politics* 30, no. 2 (January 1978): 167–214; George H. Quester, *Offense and Defense in the International System* (New York: John Wiley, 1977); Stephen Van Evera, "Offense, Defense, and the Causes of War," *International Security* 22, no. 4 (Spring 1998): 5–43; Charles

often worry about emerging military technologies, as happened with cruise missiles, cyber weapons, remotely piloted aircraft (or drones), artificial intelligence, lethal autonomous weapons, and hypersonic missiles, among others.[2] Perceptions, not factual assessments, often inform such concerns, however: academics, observers, and policymakers tend to assume emerging and disruptive technologies yield an offensive advantage without investigating whether this is empirically true.[3] Only recently have some academics started to question some of these perceptions, but their attention has been limited to cyber weapons, leaving other emerging technologies relatively untouched.[4]

In this article, we contribute to this debate by investigating whether armed drones shift the offense–defense balance (ODB) in the air domain—that is, whether drones "will always get through," to paraphrase a famous statement about bombers from the 1930s.[5] We limit our analysis to armed drones with a maximum takeoff weight above 600 kilograms: drones that belong to the categories of Medium Altitude Long Endurance (MALE) and High Altitude Long Endurance (HALE).[6] We do not consider mini- and microdrones because of their limited range and payload, which reduce their effectiveness, at most, to the tactical level. Compared to other emerging technologies, armed drones have been employed extensively in conflicts, especially over the past twenty-five years, and they have already spread to many countries—which makes them a current and pressing reality, not a distant possibility.[7] Despite the extensive attention they have received, no work in security studies and international relations has investigated whether current- and next-generation drones yield an offensive advantage. Conversely, the existing debate has largely

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L. Glaser and Chaim Kaufmann, "What Is the Offense-Defense Balance and Can We Measure It?" *International Security* 22, no. 4 (Spring 1998): 44–82.

[2] Todd S. Sechser, Neil Narang, and Caitlin Talmadge, eds., *Emerging Technologies and International Stability* (New York: Routledge, 2022).

[3] For a discussion, see Stephen Van Evera, "The Cult of the Offensive and the Origins of the First World War," *International Security* 9, no. 1 (Summer 1984): 58–107; Jack Snyder, "Civil-Military Relations and the Cult of the Offensive, 1914 and 1984," *International Security* 9, no. 1 (Summer 1984): 108–46.

[4] See, for example, Erik Gartzke and Jon R. Lindsay, "Weaving Tangled Webs: Offense, Defense, and Deception in Cyberspace," *Security Studies* 24, no. 2 (April–June 2015): 316–48. For an exception outside the cyber domain, see Jon R. Lindsay, "Demystifying the Quantum Threat: Infrastructure, Institutions, and Intelligence Advantage," *Security Studies* 29, no. 2 (April–May 2020): 335–61; Cameron L. Tracy and David Wright, "Modelling the Performance of Hypersonic Boost-Glide Missiles," *Science & Global Security* 28, no. 3 (September–December 2020): 135–70.

[5] In 1932, the British statesman Stanley Baldwin gave a speech to the British Parliament in which he stated that "there is no power on earth that can protect [the man in the street] from being bombed. Whatever people may tell him, the bomber will always get through." Quoted in Uri Bialer, *The Shadow of the Bomber: The Fear of Air Attack and British Politics, 1932–1939* (London: Royal Historical Society, 1980), 14.

[6] This is Class III of the *The Drone Databook*. Dan Gettinger, *The Drone Databook* (Annandale-on-Hudson, NY: Center for the Study of the Drone at Bard College, October 2019), v, https://dronecenter.bard.edu/files/2019/10/CSD-Drone-Databook-Web.pdf.

[7] Michael C. Horowitz, Joshua A. Schwartz, and Matthew Fuhrmann, "Who's Prone to Drone? A Global Time-Series Analysis of Armed Uninhabited Aerial Vehicle Proliferation," *Conflict Management and Peace Science* 39, no. 2 (March 2022): 119–42.

relied on untested assumptions, such as that drones are difficult to detect for air defense systems and, therefore, the former favor offensive military operations. Some have questioned these assumptions, but they have provided statements, not explanations. As a result, the academic and policy debate on drones is fraught with unsubstantiated and contradictory claims that impede a correct understanding of this technology. In other words, the drone debate suffers from some of the same pathologies that plagued the academic debate on the ODB: rather than investigating whether technological change affects the ease of attacking or defending (the ODB as a dependent variable), both literatures have assumed that technology has such an effect. Starting from this assumption, they have then studied the implications of a change in the ease of attacking or defending for world politics (the ODB as an independent variable).[8]

To conduct our analysis, we have first translated existing concerns about drones into testable propositions and then identified what would support such concerns: a major shift in the ODB either toward the offense or to offense dominance. Given the land warfare bias of the literature on the ODB, we have then adapted the parameters the literature uses to measure offensive-enhancing technological change (mobility and armor) so that they can be used to analyze air warfare (avoidance and saturation of enemy air defense systems). Subsequently, to investigate empirically whether drone technology does or will change the ODB against state-of-the-art air defense systems, we have turned to relevant disciplines such as radar engineering, electromagnetism, signal processing, and air defense operation. Our analysis is divided between current-generation drones and next-generation drones.

With regard to current-generation drones, we find that they do not yield an offensive advantage against current-generation air defense systems. Allegedly, three features of these drones endow them with an offensive advantage: their small size, slow speed, and low altitude are thought to lower the range at which drones can be detected and hence lessen the probability that they are intercepted. In fact, small size has relatively limited benefits on the range of detection. Similarly, slow cruise speed can be addressed by changing the filtering functions of air defense systems—radars generally ignore slow-moving objects, as they are unlikely to be potential threats. Finally, the effectiveness of flying at low altitude decreases significantly as the elevation of radars increases (for example, through radar masts, radars atop buildings or mountains, and airborne radars). In sum, current-generation drones possess features that are effective against only some but not all current-generation ground and airborne systems and sensors, and therefore will not be successful, systematically,

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[8] Stephen Biddle, "Rebuilding the Foundations of Offense-Defense Theory," *Journal of Politics* 63, no. 3 (August 2001): 742.

against countries that possess state-of-the-art air defenses—that is, integrated air defense systems (IADS).

With regard to next-generation drones, the existing debate has focused only on how technological change will affect the offense (drone technology) while ignoring its implications for the defense (air defense systems). This neglect leads to biased conclusions, as it relies on the unwarranted assumption that the capabilities of air defense technologies will remain constant. Air defense systems, however, depend on technologies that have experienced dramatic improvements in recent years, and that promise to advance even further in the future—such as the capacity to collect a larger quantity of more accurate and more diverse data (sensor acuity, diversity of sensors, and multisensor connectivity), to store and access in real time a larger volume of data (big data), and to process more effectively and efficiently a larger volume of data (machine learning).[9] In fact, when applied to the submarine realm, some scholars argue that these very technological transformations will drastically strengthen the defense and lead to so-called ocean transparency.[10] Although we cannot make any specific prediction about the future, our analysis suggests caution against taking for granted that next-generation drones will have an offensive advantage against next-generation air defenses.

Our article makes several contributions that go beyond the specific case of drones and speak to broader debates in security studies and international relations theory. First, our article corrects a central problem in the literature on the ODB: its bias for land warfare. This bias is particularly important because criticisms of the ODB have focused on land warfare only, neglecting other domains such as air and naval warfare.[11] Because of the differences between the air and land domains, however, it is not possible to apply the lessons of the latter to the former. Despite the logical and empirical problems critics point to, the ODB provides a simple but useful heuristic for understanding whether and how the relative ease of attacking vis-à-vis defending in the air domain varies as a result of technological change. And if this outcome is not investigated empirically, analysts, the media, observers, and policymakers might be tempted to rely on unwarranted assumptions, to derive simplistic assessments, and to draw unsubstantiated conclusions.

Second, our article shows that to understand the effect of technological change on the military balance, we need to assess, systematically, the implications for both offensive and defensive technologies. Our article thus

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[9] Erik Brynjolfsson and Andrew McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies* (New York: W. W. Norton, 2014).

[10] Bryan Clark, *The Emerging Era in Undersea Warfare* (Washington, DC: Center for Strategic and Budgetary Assessments [CSBA], 2015).

[11] For a discussion, see John R. Carter, *Airpower and the Cult of the Offensive* (Maxwell Air Force Base, AL: Air University Press, 1998), 6; Eugene Gholz, "No Man's Sea: Implications for Strategy and Theory" (paper presented at the annual conference of the International Studies Association, 16–19 March 2016, Atlanta, GA).

corrects a contradiction in the debate on emerging technologies and international stability, which often selectively and inconsistently makes assumptions about the impact of technology on weapon systems and military platforms. For example, we are told that advances in technologies such as quantum radar will cancel the offensive advantage of stealth jet fighters.[12] At the same time, however, we are also told that less sophisticated emerging aerospace technologies such as armed drones will represent a serious future threat.[13] But if quantum radars will defeat stealth, there is no intuitive reason why unsophisticated drones will have a future offensive advantage.

Third, our article shows the promise of exploring disciplines outside international relations and political science for addressing pressing academic and policy questions. To fully understand the implications of new weapons, we need to grasp their technical capabilities and limitations. As technology comes to play an ever-increasing role in modern societies, social scientists must incorporate insights from the natural sciences and engineering disciplines. Without such interdisciplinarity, contributing to important policy debates, such as those about arms control, defense acquisition, investments in research and development, and force structure, will become increasingly more difficult.

Fourth, this article also brings attention to air defense. As historian Kenneth P. Werrell has put it, "Readers are more interested in the aircraft than the weapons that bring them down."[14] This bias is evident also among scholarly works. Radar is the key technology of modern air defense systems, and it is widely credited for having played a decisive role in defeating Nazi Germany in the Battle of Britain and in the Battle of the Atlantic.[15] Similarly, surface-to-air missiles dramatically enhanced the effectiveness of air defense systems by making high-altitude flight too dangerous even for the most advanced US aircraft, such as the B-52 Stratofortress and the U-2 Dragon Lady, and they forced the cancelation of the XB-70 Valkyrie.[16] Yet political scientists have paid little attention to these two transformative technologies.[17] This neglect is particularly evident when compared to nuclear weapons and cyber weapons, especially considering that during

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[12] Brandon Specktor, "Quantum Radar Could Make Stealth Technology Obsolete," *LiveScience*, 20 April 2018; Kyle Mizokami, "How Quantum Radar Could Completely Change Warfare: You've Heard of Stealth Aircraft—Now Meet Stealth Radar," *Popular Mechanics*, 26 August 2019.

[13] James Marson and Brett Forrest, "Armed Low-Cost Drones, Made by Turkey, Reshape Battlefields and Geopolitics," *Wall Street Journal*, 3 June 2021; Agnes Callamard and James Rogers, "We Need a New International Accord to Control Drone Proliferation," *Bulletin of Atomic Scientists*, 1 December 2020, https://thebulletin.org/2020/12/we-need-a-new-international-accord-to-control-drone-proliferation/.

[14] Kenneth P. Werrell, *Archie to SAM: A Short Operational History of Ground-Based Air Defense* (Maxwell Air Force Base, AL: Air University Press, 2005), xix.

[15] According to some, radar "won" the Second World War. Robert Buderi, *The Invention That Changed the World: How a Small Group of Radar Pioneers Won the Second World War and Launched a Technical Revolution* (New York: Touchstone, 1996), 15.

[16] Steven J. Zaloga, *Soviet Air Defence Missiles: Design, Development and Tactics* (London: Jane's Information Group, 1989), 19.

[17] For exceptions among academic publications, see Stephen Biddle and Ivan Oelrich, "Future Warfare in the Western Pacific: Chinese Antiaccess/Area Denial, U.S. AirSea Battle, and Command of the Commons in East

World War II investments in research and development in radar were larger than in the Manhattan Project ($2.5 billion versus $2 billion, respectively), and that the Soviet procurement of surface-to-air missile launchers in the 1950s and 1960s turned out to be fifteen times more expensive than the Manhattan Project ($30 billion).[18] The neglect of air defense is even more remarkable when we contrast it with (ballistic) missile defense, a topic of extensive interest to scholars of nuclear strategy, and one still a matter of controversy.[19] By shedding light on this topic, we thus hope to rebalance the bias in the literature toward defining technologies of the post–World War II era.

Existing Understandings

The academic and policy debate has not investigated whether technological change affects the ODB in air warfare. This lacuna plagues works on both drone warfare and the ODB.

Drone Warfare

Despite the great attention that armed drones have generated among academics, this literature has not investigated whether drones yield an offensive advantage.[20] Conversely, it has relied on either assumptions or statements.

Pessimists

Most analysts, observers, and scholars have reacted to the emergence of drones and robotics with concern, warning about the instability that the proliferation of these technologies could promote.[21] Because drones are cheaper, less sophisticated, and easier to procure than traditional weapon systems, they are thought to endow a larger number of countries with advanced military capabilities.[22] For this reason, scholars have called for stricter regulation of these technologies with the goal of limiting their diffusion.[23]

Asia," *International Security* 41, no. 1 (Summer 2016): 7–48; Steven E. Lobell, "A Granular Theory of Balancing," *International Studies Quarterly* 62, no. 3 (September 2018): 593–605.

[18] See, respectively, David F. Noble, *Forces of Production: A Social History of Industrial Automation* (New Brunswick, NJ: Transaction, 2011), 7; Zaloga, *Soviet Air Defence Missiles*, 12.

[19] Theodore A. Postol, "Lessons of the Gulf War Experience with Patriot," *International Security* 16, no. 3 (Winter 1991–1992): 119–71.

[20] Sechser et al., eds., *Emerging Technologies and Strategic Stability*.

[21] Michael Ignatieff, "Drones Give Democracies No Cause for War," *Financial Times*, 12 June 2012; Alan W. Dowd, "Drone Wars: Risks and Warnings," *Parameters* 42, no. 1 (Winter/Spring 2013): 7–16.

[22] P. W. Singer, "The Global Swarm," *Foreign Policy*, 11 March 2013; Patrick Tucker, "Every Country Will Have Armed Drones within 10 Years," *Defense One*, 6 May 2014.

[23] Micah Zenko and Sarah Kreps, *Limiting Armed Drone Proliferation*, Council Special Report no. 69 (Washington, DC: Council on Foreign Relations, June 2014); Allen Buchanan and Robert O. Keohane, "Toward a Drone Accountability Regime," *Ethics & International Affairs* 29, no. 1 (Spring 2015): 15–37.

Implicitly or explicitly, these analysts, observers, and scholars have assumed that drones yield an offensive advantage—if this were not the case, there would be little reason for concern. Most analyses and discussions, however, have not investigated whether this assumption is correct, and have simply accepted it. Starting from this assumption, such work has then concluded that war will be more likely, more frequent, and more brutal as time goes on.[24] Others have explicitly claimed that current-generation drones yield an offensive advantage. Prominent observers, for example, have argued that "enemy UAVs …, by design, are hard to detect."[25] Some academics have substantiated this point by stressing that "the offensive value of drones such as [the Reaper] is that they are almost impervious to traditional sensor systems such as joint surveillance target attack radar system (JSTARS) that are typically oriented toward larger assets."[26] Other established experts and scholars have added that drones can evade enemy detection by flying at slow speeds or at low altitudes.[27] Others still have argued that drones can more likely penetrate an enemy's airspace because they are small, produce limited radar returns, and can fly at low altitude and at slow speed.[28] These arguments are intuitive, but those advancing them have only stated that—not investigated why—size, low altitude, and slow speed yield an offensive advantage.

Finally, some scholars have acknowledged the limitations of current-generation military drones against modern air defense systems but have warned about future capabilities that might make military drones much more effective.[29] For instance, some have warned that "unlike today's high-profile UCAVs, such as the Reaper, which are propeller driven, slow, carry

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[24] Noel Sharkey, "Drone Race Will Ultimately Lead to a Sanitized Factory of Slaughter," *Guardian*, 3 August 2012; Frank Pasquale, "'Machines Set Loose to Slaughter': The Dangerous Rise of Military AI," *Guardian*, 15 October 2021.

[25] Eric Schmidt and Jared Cohen, *The New Digital Age: Transforming Nations, Businesses, and Our Lives* (New York: Vintage 2014), 208.

[26] Sarah Kreps and Sarah Maxey, "Context Matters: The Transformative Nature of Drones on the Battlefield," in *Technology and International Relations: The New Frontier in Global Power*, ed. Giampiero Giacomello, Francesco Niccolò Moro, and Marco Valigi (Cheltenham, UK: Edward Elgar, 2021), 80.

[27] John Parachini and Peter Wilson, "Drone-Era Warfare Shows the Operational Limits of Air Defense Systems," *RealClear Defense*, 2 July 2020; Paul Scharre, cited in Jonathan Marcus, "Combat Drones: We Are in a New Era of Warfare: Here's Why," *BBC News*, 4 February 2022.

[28] See, for example, Aaron Stein: "The TB2 is small, has a low RCS, and flies very slowly. For these reasons, the preferred way to deal with it would be to strike on the ground (lessons of 1973), OCA (with air-to-air missiles—lessons from 2006), and less w/ ground based SAMs (challenges w/ doppler notch)." Stein, (@aaronstein1), Twitter, 6 March 2022, https://twitter.com/aaronstein1/status/1500530128421625864?s=20&t=RlClfRBhZ0sYMTBi2MC7ew; Tayfun Ozberk, cited in H. I. Sutton, "Incredible Success of Ukraine's Bayraktar TB2: The Ghost Of Snake Island," *Naval News*, 18 May 2022; V. K. Saxena, "Obituary! Has the Reign of Cold War-Era Tanks, Guns & Howitzers Ended as Evident by Recent Eurasian Wars?" *Eurasian Times*, 6 September 2022; Bishara A. Bahbah, "Iran-Israel Drone Competition and the Changing Nature of Warfare in the Middle East," Arab Center Washington DC, 13 October 2022.

[29] Michael C. Horowitz, Sarah E. Kreps, and Matthew Fuhrmann, "Separating Fact from Fiction in the Debate over Drone Proliferation," *International Security* 41, no. 2 (Fall 2016): 38–39; Amy Zegart, "Cheap Fights, Credible Threats: The Future of Armed Drones and Coercion," *Journal of Strategic Studies* 43, no. 1 (February 2020): 6, 13n63.

comparably small payloads and have few to no capabilities for operating in contested airspace, future systems will be less dependent on human control, faster, stealthy and capable of delivering bigger payloads."[30] Others have warned along similar lines that in the future, the low cost of drones coupled with the capacity to produce them at large scale would allow for specific offensive tactics, such as saturation, aimed at overwhelming the most sophisticated air defense systems.[31] These concerns are legitimate, but they do not take into consideration advances in air defense systems.

Optimists

Other scholars have questioned the widespread belief that drones yield an offensive advantage.[32] This literature, however, has not provided a definitive analysis. Some have only stated that drones are vulnerable to air defense systems, but not explained why or how.[33] Others have provided an explanation, concluding that "because they fly at low altitudes and slow speeds … drones are highly vulnerable to enemy air defenses" without, however, testing this assertion empirically.[34] Moreover, since this explanation contradicts some of the claims drone pessimists advance, the international relations field is left wondering whether slow speed and low altitude are in the end an advantage or a disadvantage against modern air defenses. Finally, the optimists have focused on current capabilities only. We thus do not know whether future drones will still be vulnerable to air defense systems.

Offense–Defense Balance

The literature on the ODB does not aid in understanding whether drones yield an offensive advantage either, and more generally whether technological change shifts the ODB in air warfare.[35] To start, the existing

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[30] Jürgen Altmann and Frank Sauer, "Autonomous Weapon Systems and Strategic Stability," *Survival* 59, no. 5 (October–November 2017): 122.

[31] T. X. Hammes, "The Future of Warfare: Small, Many, Smart vs. Few & Exquisite?" *War on the Rocks*, 16 July 2014, https://warontherocks.com/2014/07/the-future-of-warfare-small-many-smart-vs-few-exquisite/; Irving Lachow, "The Upside and Downside of Swarming Drones," *Bulletin of the Atomic Scientists* 73, no. 2 (2017): 96–101; David Hambling, "The Next Era of Drones Will Be Defined by 'Swarms,'" *BBC*, 26 April 2017, https://www.bbc.com/future/article/20170425-were-entering-the-next-era-of-drones.

[32] Michael P. Kreuzer, *Drones and the Future of Air Warfare: The Evolution of Remotely Piloted Aircraft* (London: Routledge, 2016), 15, 145.

[33] Andrea Gilli and Mauro Gilli, "The Diffusion of Drone Warfare? Industrial, Organizational, and Infrastructural Constraints," *Security Studies* 25, no. 1 (January–March 2016): 80. For an exception, see André Haider, *Remotely Piloted Aircraft Systems in Contested Environments: A Vulnerability Analysis* (Kalkar, Germany: Joint Air Power Competence Centre, 2014).

[34] Horowitz et al., "Separating Fact from Fiction in the Debate over Drone Proliferation," 16.

[35] For criticisms of the ODB literature, see Stephen Biddle, *Military Power: Explaining Victory and Defeat in Modern Warfare* (Princeton, NJ: Princeton University Press, 2004); Keir A. Lieber, *War and the Engineers: The Primacy of Politics on Technology* (Ithaca, NY: Cornell University Press, 2005). For critical summaries of the offense–defense theory, see Jack S. Levy, "The Offensive/Defensive Balance of Military Technology: A Theoretical and Historical

literature has not studied the ODB as a dependent variable.[36] As a result, the only works that have studied whether technological change affects the ease of attacking vis-à-vis defending are those criticizing the ODB literature itself.[37] Moreover, both the pro- and anti-ODB literatures have focused exclusively on land warfare.[38] But the defining conditions of land warfare do not apply to air warfare. First, some of the key parameters used by the ODB literature, such as protection (armor), are of little value for air warfare, given that in the case of aircraft, the focus on armor is unintelligible.[39]

Second, some of the criticisms of the ODB apply less stringently to air warfare. Consider the impossibility of distinguishing between defensive and offensive technologies—one of the main problems of the ODB literature.[40] Though correct in general, IADS and long-range heavy bombers have very different functions and goals.[41] In fact, the real paradox of the ODB literature is its neglect of two of the past century's most revolutionary military technologies: radar (and more generally, air defense systems) and stealth.[42]

Third, in air warfare, technology is much more important than in land warfare. In contrast to the complexity of the land domain, the simplicity of its aerial counterpart offers fewer opportunities for cover and concealment, which in turn means that technology plays a more important role: staying airborne, avoiding detection, and escaping interceptions depend on technological capabilities.[43] Tellingly, in a recent coauthored article, one of the most prominent castigators of the ODB in land warfare, Stephen Biddle, embraces the logic underpinning the ODB when it comes to the air and naval domains by acknowledging that "the sky and the surface of the sea present much simpler backgrounds than the land. Land-based missiles

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Analysis," *International Studies Quarterly* 28, no. 2 (June 1984): 219–38; Sean M. Lynn-Jones, "Offense-Defense Theory and Its Critics," *Security Studies* 4, no. 4 (Summer 1995): 660–91.

[36] Biddle, "Rebuilding the Foundations of Offense-Defense Theory," 742.

[37] Biddle, "Rebuilding the Foundations of Offense-Defense Theory"; Keir A. Lieber, "Grasping the Technological Peace: The Offense-Defense Balance and International Security," *International Security* 25, no. 1 (Summer 2000): 71–104; Lieber, *War and the Engineers*. A partial exception in this regard is Karen Ruth Adams, "Attack and Conquer? International Anarchy and the Offense-Defense-Deterrence Balance," *International Security* 28, no. 3 (Winter 2003/04): 45–83.

[38] To our knowledge, the only two works that have explicitly looked at the ODB in air warfare are Stanley J. Dougherty, *Defense Suppression: Building Some Operational Concepts* (Maxwell Air Force Base, AL: Air University Press, 1992); and Carter, *Airpower and the Cult of the Offensive*.

[39] Since aircraft design imposes strict trade-offs in terms of weight and shape, the opportunities for protection are inherently limited. John P. Fielding, *Introduction to Aircraft Design* (Cambridge: Cambridge University Press, 1999), 37–44.

[40] Levy, "Offensive/Defensive Balance of Military Technology"; John J. Mearsheimer, *Conventional Deterrence* (Ithaca, NY: Cornell University Press, 1983), 25–27; Lieber, "Grasping the Technological Peace," 77–78.

[41] For this criticism when applied to land warfare, see Keir A. Lieber, "Mission Impossible: Measuring the Offense-Defense Balance with Military Net Assessment," *Security Studies* 20, no. 3 (Summer 2011): 451–59.

[42] Among the works on the ODB, to our knowledge, the only that has discussed radar (spending, however, only two sentences on it), is Glaser and Kaufmann, "What Is the Offense-Defense Balance, and Can We Measure It?," 64.

[43] Martin van Creveld, *Technology and War: From 2000 B.C. to the Present* (New York: Touchstone, 1989), 229.

deployed amid a complex background thus enjoy systematic [reconnaissance, surveillance, and target acquisition] advantages against airborne or sea-surface foes."[44]

Testing the Drone Offensive Advantage

The academic and policy debate about drones relies on an unverified assumption—that drone technology yields an offensive advantage. In this section, we translate this assumption into a set of testable propositions. Since the history of air warfare is a never-ending shift between offensive-dominant and defensive-dominant technologies, we thus try to understand whether MALE drones represent a new instance of offense-enhancing technological change.[45]

Dependent Variable: Change in the Offense–Defense Balance

The ODB captures the relative ease of attacking vis-à-vis defending given state-of-the-art technology.[46] Because we are interested in understanding whether current- and next-generation drones have shifted or will shift the ODB, our dependent variable is the change in the ODB.[47]

We consider the ODB at the technical level. Changes in the ODB at the strategic level might be due to variables unrelated to technological change (such as alliances, gross domestic product, or lack of economic incentives for conquest), whereas changes in the ODB at the operational and tactical levels depend on force employment, not simply on technology.[48] Our focus is justified by the implicit assumption in the current debate that changes in the ODB at the technical level will translate into advantages at either the tactical or operational level—the development of low-observable ("stealth") technology being a prominent example.[49]

We measure change in the ODB in strict military terms: the change in the capacity of drone technology to penetrate an enemy's airspace—that is, to approach, enter, and operate in a hostile environment defended by ground- and aerial-based air defense systems so as to be able to strike their intended targets. Our approach is consistent with the scholarly concern that technological change favoring the offense will lead to "quick and

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[44] Biddle and Oelrich, "Future Warfare in the Western Pacific," 12–13.
[45] Werrell, *Archie to SAM*, xviii, 276; Dougherty, *Defense Suppression*, 9.
[46] Jervis, "Cooperation under the Security Dilemma."
[47] Biddle, "Rebuilding the Foundations of Offense-Defense Theory," 741; Lieber, *War and the Engineers*, 28; Adams "Attack and Conquer?," 50.
[48] Adams, "Attack and Conquer?," 50–51; Biddle, "Rebuilding the Foundations of Offense-Defense Theory," 747–48; Lieber, *War and the Engineers*, 28.
[49] Eliot A. Cohen, *Gulf War Air Power Survey*, vol. 2, *Operations and Effects and Effectiveness* (Washington, DC: Government Printing Office, 1993), 123.

decisive" victories.[50] Moreover, our approach avoids the inherent problems of measuring the ODB in terms of the relative cost of attacking vis-à-vis defending—which is common among works that have studied the ODB as an independent variable, but this has never been used to measure the ODB as a dependent variable.[51]

What would constitute a shift in the ODB? To answer this question, we need to start from IADS, the technology that drones have to defeat. IADS rely on multiple airborne and ground-based sensors and shooting platforms, including ground-based and airborne early warning radars, target acquisition radars, interceptor aircraft, and fixed and mobile short- and long-range air defense systems. The integration of data gathered by multiple types of sensors minimizes the probability that a target will be missed.[52] Through multiple types of shooting platforms, IADS can engage different targets at both short and long ranges as well as at low and high altitudes.[53] As a result, IADS are a formidable threat for any military aircraft.[54] For this reason, many believe that we have lived in an era of air defense dominance since the 1960s—with the exception of the introduction of stealth technology.[55]

To assess whether drones shift or will shift the ODB we need to define a threshold to establish what would constitute such a change that is consistent with existing debates. Accordingly, we focus on two types of major shifts: either toward the offense or to offense dominance. Assume the ODB is a continuous variable that goes from defense dominance to offense dominance—for example, from -100 to $+100$, with 0 being neutral balance. A major shift toward the offense would be, for example, from -80 to -30 or from -90 to -10, whereas a shift to offense dominance would be, for example, from -20 to $+30$ or from -30 to $+50$. The difference between the two types of major shifts is in the outcome they produce—that is, whether they make attacking easier relative to existing conditions (attacking

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[50] Glaser and Kaufmann, "What Is the Offense-Defense Balance, and Can We Measure It?," 48; Lieber, "Grasping the Technological Peace," 71, 81; Biddle, "Rebuilding the Foundations of Offense-Defense Theory," 747–48.

[51] On the problems of measuring the ODB, see Levy, "Offensive/Defensive Balance of Military Technology;" Lynn-Jones, "Offense-Defense Theory and Its Critics."

[52] "The Cooperative Engagement Capability," *Johns Hopkins APL Technology Digest* 16, no. 4 (1995): 377–96, https://www.jhuapl.edu/Content/techdigest/pdf/V16-N04/16-04-APLteam.pdf; Peter W. Mattes, "Systems of Systems: What, Exactly, Is an Integrated Air Defense System?" *Mitchell Forum*, no. 26 (June 2019): 1–10.

[53] *Electronic Warfare Fundamentals* (Nellis Air Force Base, NV: Air Combat Command Training Support Squadron, 2000), 1.6–1.10.

[54] John A. Tirpak, "Dealing with Air Defenses," *Air Force Magazine* (November 1999): 25–29, https://www.airforcemag.com/PDF/MagazineArchive/Documents/1999/November%201999/1199airdefense.pdf. Aircraft that have not been designed to operate in contested airspaces and that do not possess advanced electronic countermeasures have very little chance of survival against IADS. Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute, 2010), 36–53; Mark Barrett with Mace Carpenter, *Survivability in the Digital Age: The Imperative for Stealth* (Arlington, VA: Mitchell Institute, 2017), 30.

[55] Grant, *Radar Game*, 36–46.

is easier than it used to be) or easy in absolute terms (attacking is easier than defending).

The most intuitive way to appreciate the difference between these two types of shifts of the ODB is by looking the range at which modern radars can detect an incoming aircraft. Such range of detection affects the reaction time available for IADS to identify, locate, and engage an intruder after it has been detected. Consider technological change that reduces the range of detection by 100 km. Its effect on the ODB will depend on the baseline conditions. If technological change reduces the range of detection from 300 km to 200 km, it will shrink available reaction time for air defenses, which means that it shifts the balance toward the offense (it makes attacking easier). But it will not shift the balance to offense dominance, as 200 km still gives enough reaction time to air defenses. If technological change reduces the range of detection from 130 km to 30 km, it will shift the balance to offense dominance (it makes attacking easy), as 30 km might not leave sufficient time for air defenses to identify, locate, and engage an intruder.

Independent Variable: Technological Change

Our independent variable is technological change induced by current- and next-generation drones. Given that the drone revolution is seen as shifting state-of-the-art technology toward the offense or to offense dominance, we consider technology as a systemic variable.[56] Hence, we are not interested in assessing the relative capabilities of a dyad of states or in understanding the effects on battle outcomes of how states employ drones.[57]

In land warfare, technological change that increases the capacity to advance through enemy fire strengthens the offense.[58] We have applied this principle to air warfare and identified two causal mechanisms that are consistent with the drone offensive advantage thesis: avoidance-enhancing and saturation-enhancing.[59] Avoidance-enhancing technological change lowers the probability that aircraft will be detected and intercepted by enemy air defense systems (stealth technology belongs to this category). Saturation-enhancing technological change increases the probability that aircraft will numerically overwhelm enemy air defense systems: though some aircraft will be shot down, others will still be able to get through, as an air defense system can engage only a limited number of targets at any given time, and it possesses a finite number of munitions.

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[56] Lynn-Jones, "Offence-Defense Theory and its Critics," 665–67.

[57] Glaser and Kaufmann, "What Is the Offense-Defense Balance, and Can We Measure It?," 46.

[58] Lieber, "Grasping the Technological Peace," 78–90; Lieber, *War and the Engineers*, 40–41.

[59] Dougherty, *Defense Suppression*, 4–7; Carter, *Airpower and the Cult of the Offensive*, 1–4, 36–39.

Expectations about Current- and Next-Generation Drones

With our analysis, we test a set of hypotheses derived from the existing debates about whether specific features of current- and next-generation drones shift the ODB. We investigate whether drones shift the ODB toward the offense and to offense dominance. The null hypothesis is that drones do not change the ODB.

Current-Generation Drones

For current-generation drones, we look at three features that are often discussed as being a source of offensive advantage against current-generation air defenses: their small size, low-altitude flight, and slow speed. If existing understandings are correct, these three features, individually or jointly, should significantly reduce the range at which current-generation drones can be detected, thus decreasing the available reaction time for air defense, and thus lowering the probability of interception.[60] In other words, these three features should, individually or jointly, increase the probability that drones can successfully penetrate and carry out strikes within an enemy's airspace defended by IADS.[61] Our focus on size, altitude, and speed is particularly warranted because they are the very same aspects that, in the 1990s and 2000s, led many to warn about the threat cruise missiles posed.[62]

Next-Generation Drones

For next-generation drones, we look at two alternative developments that, according to existing understandings, will give them an offensive advantage against next-generation air defense systems: the application of stealth technology to drones aimed at reducing the range at which they can be detected, and the employment of drones in large enough numbers to saturate an enemy's air defenses. If existing understandings are correct, either of these two approaches should significantly increase the probability that drones successfully penetrate an enemy's air defense systems. Stealth technology entails that drones will have qualitative superiority, whereas saturation tactics entail that drones will have quantitative superiority against IADS.

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[60] To be successful, IADS need to complete a strict sequence of critical steps that entail, among others, the detection, identification, tracking, and eventual engagement of enemy intruders (known as the "kill-chain"). Mattes, "Systems of Systems," 3–7.

[61] As current-generation drones do not possess electronic warfare capabilities, we focus on the range of detection.

[62] John C. Toomay, "Technical Characteristics" in *Cruise Missiles: Technology, Strategy, Politics*, ed. Richard K. Betts (Washington, DC: Brookings Institution, 1981), 31.

Current-Generation Drones against Current-Generation Air Defenses

In this section we investigate whether current-generation drones have an offensive advantage against current-generation air defenses. Our analysis does not support existing concerns.

Size and Detection

Does size affect the range at which drones can be detected, so much so that enemy air defense systems will be significantly less likely to intercept them (ODB shift toward the offense) or unlikely to intercept them at all (shift to offense dominance)? Although size does affect the range of radar detection, the current debate overstates the importance of size and underestimates the other, more important, determinants of radar reflection—primarily the frequency of the radar pulse, as well as the shape and orientation of the object with respect to the incoming radar beams.

The range at which an object will be detected (and hence the probability that it will be detected at any given range) depends on how much electromagnetic energy it will reflect back when illuminated by a radar beam. Such reflected energy (radar echo) is measured in terms of radar cross section (RCS), which is "the size of a sphere which would reflect the same amount of radar energy as the aircraft … measured. The RCS in square meters is then the area of a circle of the same diameter as this imaginary sphere."[63] The bigger the RCS of an object, the farther the range at which it can be detected, and hence the more time available for a country's air defense system to identify, geolocate, track, and eventually engage the incoming threat. The size of an object does influence its RCS. But the relationship between size, RCS, and detection range is much weaker than drone pessimists suggest.

To start, military drones of the MALE category are not small, as their wingspan is longer than that of jet fighters. A Bayraktar TB2 has a length of 6.5 m and a wingspan of 12 m, the US-made MQ-9A Reaper has a length of 11 m and a wingspan of 20 m, and the Iranian-made Shahed-129 has a length of 8 m and a wingspan of 16 m. In comparison, jet fighters such as the F-16 Fighting Falcon or F-18 Hornet are respectively 15 m and 17 m long, with wingspans of 9.5 m and 11.5 m.[64] MALE UAVs are thus not

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[63] Doug Richardson, *Stealth: Deception, Evasion, and Concealment in the Air* (New York: Orion, 1989), 27. For a more technical discussion, see Daniel P. Meyer and Herbert A. Mayer, *Radar Target Detection: Handbook of Theory and Practice* (New York: Academic Press, 1973), 36–82.

[64] See, respectively, the technical specifications provided by the producers. For the F-16 Fighting Falcon, see Lockheed Martin's website: https://www.lockheedmartin.com/en-us/products/f-16.html; for the F-18 Super Hornet, see Boeing's website: https://www.boeing.com/history/products/fa-18-hornet.page; for the TB2, see Baykatar's website: https://www.baykartech.com/en/uav/bayraktar-tb2/; for the MQ-9A Reaper, see General Atomic's website: https://www.ga-asi.com/remotely-piloted-aircraft/mq-9a; for the Shahed-129, see the

much smaller than jet fighters. One might point out that MALE UAVs have a leaner shape compared to traditional crewed military aircraft, that their wingspan is not informative about their size, or that in the near future, their wingspan will be much shorter. To address these objections, we investigate whether size affects the probability of detection and/or interception.

First, existing debates overstate the importance of size in determining the RCS of military drones. The RCS of an object is not a function of solely its size, as the existing debate implies; it is a function of the relationship between the wavelength of the radar pulse and the size of the target.[65] Hence, radars operating at different wavelengths will produce different radar echoes when illuminating an incoming UAV, and whereas some of these echoes will be small, others will be quite significant.[66] Radar waves go from millimetric (0.001 m) to hectometric (100 m) in length. Radars tasked with long-range detection emit long wavelength pulses (low frequency); radars tasked with target acquisition and tracking emit short wavelength pulses (high frequency).[67] With the exception of extremely small objects, size has little to no effect on diminishing either the probability of detection or the probability of target acquisition and tracking.[68] For long-range detection radars, small target size plays no significant role, save for extreme cases where the wavelength of the incoming pulse is several times larger than the span (length or width) of the target.[69] These radars operate at centimetric, metric, and decametric wavelengths, which means the wavelength of the radar pulse will be either smaller, similar, or slightly larger than an incoming UAV, and hence the dominant determinants of the RCS will be the overall shape and orientation of the UAV, not its size.[70] The size of an object is not relevant for target acquisition and fire-control radars either.[71] These radars operate at centimetric wavelengths, and in this case, the RCS "tends to be dominated by specular [that is, mirror-like] reflections and by reflections due to edges and surface discontinuities."[72] In practical terms,

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information provided in Babak Taghvaee, "Shahed 129 Heads Iran's Armed UAV Force," *Aviation Week & Space Technology*, 27 July 2017.

[65] S. S. Swords, *Technical History of the Beginnings of Radar* (Hertz, UK: Institution of Engineering and Technology, 2008), 7–8.

[66] Oleg I. Sukharevsky, ed., *Electromagnetic Wave Scattering by Aerial and Ground Radar Objects* (Boca Raton, FL: CRC Press, 2014), 139–51.

[67] Mark A. Richards, *Fundamentals of Radar Signal Processing*, 2nd ed. (New York: McGraw-Hill, 2014), 6–7.

[68] The primary source of radar reflection of a target will be different features, depending on whether the incoming wavelength is smaller, equal to, or larger than the object of interest. Simon Kingsley and Shaun Quegan, *Understanding Radar Systems* (Mendham, NJ: SciTech, 1999), 33.

[69] Kingsley and Quegan, *Understanding Radar Systems*, 33; Andrew M. Sessler, John M. Cornwall, Bob Dietz, Steve Fetter, Sherman Frankel, Richard L. Garwin, Kurt Gottfried, Lisbeth Gronlund, George N. Lewis, Theodore A. Postol, et al., *Countermeasures: A Technical Evaluation of the Operational Effectiveness of the Planned US National Missile Defense System* (Cambridge, MA: Union of Concerned Scientists, April 2000), 131–43.

[70] Kingsley and Quegan, *Understanding Radar Systems*, 33; Sessler et al., *Countermeasures*, 132.

[71] Kingsley and Quegan, *Understanding Radar Systems*, 33.

[72] Sessler et al., *Countermeasures*, 131.

the radar pulses target acquisition radars emit will be scattered by small details such as fasteners not perfectly aligned to the body of the aircraft, protuberances or angles such as those produced by vertical fins, and horizontal stabilizers.[73] Consider that when illuminated by a target acquisition radar, an intersection among three squares with sides just 15 cm long will produce an RCS of 21 m^2—which can be detected between 200 km and 300 km away.[74]

Second, the alleged low RCS of military drones is neither a significant improvement compared to existing aerospace technologies, nor sufficient per se to defeat state-of-the-art air defense systems. UAVs like the Predator or the Reaper have a frontal RCS that, according to computer simulations, ranges between 0.01 m^2 and 1 m^2—which is remarkable given that an RCS below 0.1 m^2 is generally considered in the "stealth" category.[75] Yet these simulations do not include the undercarriage missiles UAVs carry and their electro-optical (E/O) camera—which are significant sources of backscattering (this is why, in stealth aircraft, missiles are stored internally and the E/O camera is shielded by a special radar-deflecting casing).[76] Thus, the real frontal RCS of MALE UAVs is very likely larger than these simulations' lowest estimates. Moreover, some conventional aircraft, such as the F-16C, the Rafale, and the B-1B Lancer, allegedly, have a similar RCS, whereas cruise missiles and stealth aircraft have much lower RCSs.[77] Even if the RCS of MALE UAVs were slightly smaller than some state-of-the-art aerospace technologies, small reductions in RCS, by themselves, would not be sufficient to significantly reduce the range at which drones can be detected—either to make their interception more difficult or unlikely. The reason being that the relationship between RCS and range of radar detection is less than linear.[78] A 50% reduction of the RCS of an aircraft decreases the range at which it can be detected by only 15%; a 95% RCS reduction decreases detection range by 50%; and a 99% RCS reduction decreases detection range by 67%.[79] Consider that the range of detection

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[73] Ben R. Rich and Leo Janos, *Skunk Works: A Personal Memoir of My Years at Lockheed* (New York: Little, Brown, 1994), 69.

[74] See, respectively, Sessler et al., *Countermeasures*, 132; Carlo Kopp, "NIEMI/Antey S-300V Air Defence System," Air Power Australia Technical Report APA-TR-2006-1202 (2012).

[75] As stated above, the RCS of an aircraft varies with frequency. Here we are reporting the values for fire-control radars (X-band). Ivan Ryapolov et al., "Radar Cross-Section Calculation for Unmanned Aerial Vehicle," in *2014 International Conference on Mathematical Methods in Electromagnetic Theory* (Piscataway, NJ: IEEE, 2014), 258–61, https://doi.org/10.1109/MMET.2014.6928747. For a scale of RCS, see Grant, *Radar Game*, 35.

[76] "F-35 Lightning II Electro-Optical Targeting System (EOTS)," Lockheed Martin, 30 November 2020, https://www.lockheedmartin.com/en-us/products/f-35-lightning-ii-eots.html.

[77] David K. Barton and Sergey A. Leonov, *Radar Technology Encyclopedia* (London: Artech House, 1998), 363; Fred E. Nathanson et al., *Radar Design Principles: Signal Processing and the Environment*, 2nd ed. (Mendham, NJ: SciTech, 1999), 176; Fielding, *Introduction to Aircraft Design*, 42.

[78] J. C. Toomay and Paul J. Hannen, *Radar Principles for the Non-Specialist*, 3rd ed. (Norwich, NY: SciTech, 2004), 1–14.

[79] Bill Sweetman, *Stealth Aircraft: Secrets of Future Airpower* (Osceola, WI: Motorbooks, 1986), 37; William F. Bahret, "The Beginnings of Stealth Technology," *IEEE Transactions on Aerospace and Electronic Systems* 29, no. 4 (October 1993): 1378.

for Russian early warning radar will be up to 350 km for an aircraft with an RCS of 10 m^2, up to 200 km for an aircraft with an RCS of 1 m^2, and up to 120 km for an aircraft with an RCS of 0.1 m^2.[80] Along the same lines, surveillance radar will be able to track a small object such as a bird between 30 km and 50 km, whereas fire-control radar will track them between 15 km and 30 km.[81] This is why stealth technology aims at reducing the RCS by several orders of magnitude (that is, a reduction of 1,000 or 10,000 times) to achieve significant reduction in the range of detection.[82] Finally, modern radar systems rely on advanced sensors and advanced signal processing techniques that permit better discrimination of objects with extremely low RCSs, and hence detection and tracking of them at long ranges.[83] The Russian S-400 Triumf air defense system, for instance, is allegedly capable of detecting and tracking, at distance, objects with an RCS of 0.02 m^2.[84] This is why a stealth aircraft such as the American F-35 Lightning II, whose frontal RCS is thought to be 0.0015 m^2, possesses integrated and automated jamming capabilities aimed at supporting itself within a denied environment.[85]

Fourth, existing discussions about the low RCS of UAVs focus on the frontal RCS only. This is reasonable, since aircraft penetrating enemy territory will likely be illuminated from the front by radars searching for intruders. IADS, however, rely on multiple ground-based and airborne radars providing overlapping coverage, which allow them to illuminate incoming vehicles from different directions; this is particularly relevant because the RCS of UAVs will vary quite significantly from different angles of incidence (both in azimuth and elevation).[86] For most aircraft, the RCS is lowest from the front.[87] From the side and rear, however, the RCS will increase markedly, as flat surfaces like vertical fins, angles between the

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[80] Kopp, "NIEMI/Antey S-300V."

[81] David Lynch Jr., *Introduction to RF Stealth* (Raleigh, NC: SciTech, 2004), 46–51. Early warning radars operate in the VHF frequency band (30–299 megahertz (MHz) frequencies, 10–1 m wavelength), which provides long-range detection but low resolution. Surveillance radars operate in the S-band (2–4 gigahertz (GHz), 15–7.5 cm) and L-band (1–2 GHz, 30–15 cm), which provide higher resolution, but shorter range in comparison to VHF. Fire-control radars operate in the X-band (8–12 GHz, 3.75–2.5 cm), which provide slightly shorter range but much higher resolution than the S-band and L-band.

[82] Alan Brown, cited in Rich and Janos, *Skunk Works*, 81.

[83] Kingsley and Quegan, *Understanding Radar Systems*, 310–11; George W. Stimson, *Introduction to Airborne Radar*, 2nd ed. (Mendham, NJ: SciTech, 1998), 10–11; George W. Stimson et al., *Stimson's Introduction to Airborne Radar*, 3rd ed. (Mendham, NJ: SciTech, 2014), 597–696; Richards, *Fundamentals of Radar Signal Processing*, 215–94.

[84] Carlo Kopp, "Almaz S-300P Almaz-Antey S-400 Triumf," Air Power Australia Technical Report APA-TR-2006-1201 (December 2006), http://www.ausairpower.net/APA-Grumble-Gargoyle.html. See also Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, DC: CSBA, 2015), 14.

[85] See Professor David Jenn, "RCS Reduction (Chapter 7)," slide 3, course "EC4630 Radar and Laser Cross Section," Naval Postgraduate School (Fall 2011), http://faculty.nps.edu/jenn/EC4630/RCSredux.pdf.

[86] The azimuth angle refers to the side of the target illuminated by the radar (whether front, side, or rear). The elevation angle is the difference in elevation between the radar and the target.

[87] This is a function of several factors, including the country's shape, the location of radars, and path profile chosen by mission planners.

fuselage and the wings, and engine blades are significant sources of radar backscattering.[88] This means that radar returns will reveal the presence of the MALE UAV to the enemy's air defense systems, which will be able to acquire, track, and engage the target.[89]

Finally, discussions about the small RCS of military UAVs tend to neglect that low observability to enemy sensors also requires radio silence or, more generally, radio-emission control.[90] But UAVs, by definition, need to receive and transmit information, primarily video footage that permits the ground station to carry out the intended operation.[91] Such radio transmissions, in turn, can be detected and jammed.[92] Similarly, other indirect ways to detect enemy aircraft exist, such as exploiting the vulnerabilities in their identification friend or foe devices.[93]

Low Altitude and Detection

Does flying at low altitude significantly reduce the range at which drones will be detected, so much so that enemy air defense systems will be less likely to intercept them (shift toward the offense) or not be able to intercept them at all (shift to offense dominance)? In principle, this argument is correct, but it neglects that the tactic is not novel compared to existing military aircraft, exaggerates its potential benefits, understates its inherent challenges, and disregards the main risks for any aircraft flying at low altitude—exposing itself to barrage from antiair artillery.

Aircraft can delay detection by enemy radar by flying at low altitude. This is encapsulated by the metaphor "flying under the radar" (also known as "terrain masking" or "ground-hugging").[94] Radar beams travel in a line of sight like all electromagnetic waves, such as light and laser, do. Because of the curvature of the earth, radar beams cannot illuminate objects at long range that fly below a given altitude (this area is known as "radar shadow"). For instance, a ground-based radar will detect an aircraft flying at a 10 km altitude at more than 400 km in distance, but it will detect an aircraft flying at a 200 m altitude at only 80 km in distance.[95] Low-altitude flight

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[88] Sukharevsky, *Electromagnetic Wave Scattering*, 75–83, 151–60.

[89] Grant, *Radar Game*, 40–44.

[90] For a discussion, see "Introduction to Radar Systems: Target Radar Cross Section," course slides, MIT Lincoln Laboratory (n.d.), https://www.ll.mit.edu/sites/default/files/outreach/doc/2018-07/lecture%204.pdf.

[91] Benjamin S. Lambeth, *Air Power against Terror: America's Conduct of Operation Enduring Freedom* (Santa Monica, CA: RAND Corp., 2005), 279.

[92] Lynch, *Introduction to RF Stealth*, 529–31; Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*, 26.

[93] Marshall L. Michel III, *Clashes: Air Combat over North Vietnam 1965–1972* (Annapolis, MD: Naval Institute Press, 1997), 100–101.

[94] *Electronic Warfare Fundamentals*, 2.9–2.14, 6.23–6.26.

[95] The altitude of the radar shadow is a function of distance between the radar and the target, and of their respective elevations. As the aircraft approaches the radar, the altitude below which it is safe from detection

thus significantly delays detection by enemy radar systems. Yet this approach has some limitations and poses inherent challenges and risks.

First, low-altitude flight is not a new capability drones introduced, which means that by employing this tactic, drones do not shift the ODB toward the offense in comparison to existing aerospace technologies. Since World War II, countries have employed this tactic to deal with enemy ground-based radars.[96] In the 1970s, the United States made major advances in navigation technology that made low-altitude flight much safer.[97] Since then, navigation technologies have further improved, and nowadays plenty of aircraft can fly at low altitude, including fourth- and fifth-generation jet fighters such as the F-16, the F-15, the F-35; variable-wing bombers such as the Tu-160 Blackjack and the B-1B Lancer; and cruise missiles.[98]

Second, flying at low altitude is effective only against ground-based radars, not against airborne radars: as the elevation of the radar increases, so does its range of detection against low-flying aircraft, and the benefit of taking advantage of the curvature of the earth shrinks significantly and eventually vanishes.[99] A multiplicity of airborne assets endowed with so-called look-down shoot-down radar provide this capability, including Airborne Early Warning and Control aircraft and jet fighters.[100] Moreover, over the past twenty years, countries such as the United States have invested in additional airborne systems that provide persistent surveillance and have lower operational and maintenance costs, such as radars mounted on aerostat, on modified commercial aircraft, and on satellites, as well as on MALE and HALE UAVs.[101] The latter deserve special attention: military drones could also serve as an effective and affordable solution for persistent surveillance and early warning.[102] Prominent experts, for instance, have advised countries that have MALE and HALE UAVs in their inventory to deploy fleets of drones to maintain real-time, persistent situational awareness in key strategic areas at an affordable price.[103]

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will shrink. Congressional Budget Office, *B-1B Bomber and Options for Enhancements* (Washington, DC: US Government Printing Office, 1988), 89–90.

[96] See, for example, C. R. Anderegg, *Sierra Hotel: Flying Air Force Fighters in the Decade after Vietnam* (Washington, DC: Air Force History and Museums Program, United States Air Force, 2001).

[97] Stimson, *Introduction to Airborne Radar*, 38–40.

[98] Thomas G. Mahnken, *The Cruise Missile Challenge* (Washington, DC: CSBA, 2005), 19–22.

[99] William H. Zinger and Jerry A. Krill, “Mountain Top: Beyond-the-Horizon Cruise Missile Defense,” *Johns Hopkins APL Technical Digest* 18, no. 4 (1997): 501–20; Donald L. Clark, “Early Advances in Radar Technology for Aircraft Detection,” *Lincoln Laboratory Journal* 12, no. 2 (2000): 167–80.

[100] On the importance of the look-down shot-down radar, see David E. Hoffman, *The Billion Dollar Spy: A True Story of Cold War Espionage and Betrayal* (New York: Doubleday, 2015), 57–61.

[101] *National Cruise Missile Defense: Issues and Alternatives* (Washington, DC: Congressional Budget Office, 2021).

[102] For an exception, see Eugene Gholz, “Nothing Much to Do: Why America Can Bring All Troops Home from the Middle East,” *Quincy Paper* no. 7 (June 2021): 1–54.

[103] Thomas G. Mahnken, Travis Sharp, and Grace B. Kim, *Deterrence by Detection: A Key Role for Unmanned Aircraft Systems in Great Power Competition* (Washington, DC: CSBA, 2020).

Third, ground-based air defense systems are not impotent against low-altitude threats. During the Cold War, for example, the United States fielded an electromagnetic "fence" between the radar outposts of the Distant Early Warning Line to address the risk of low-flying Soviet bombers.[104] Similarly, radars placed atop buildings, cliffs, or mountains significantly enhance the range of detection of low-flying targets—in this way the United States carried out exercises in the 1990s showing the successful engagement of incoming drones and cruise missiles flying at low altitude.[105] Finally, the employment of a mast-mounted radar permits an increase in the range of detection of low-flying objects in areas without hills or buildings.[106] This feature does not fully address the threat of low-flying vehicles, but it increases the range of detection for areas that have no alternative option, thus increasing the probability of successful interception.[107]

Fourth, against a country that deploys a layered defense system with long-range, middle-range, short-range, and man-portable air defense systems (LORAD, MEADS, SHORAD, and MANPADs), drones flying at low altitude will be exposed to a variety of sensors and shooters that, individually or jointly, can detect, track, engage, and damage/destruct them well before they can get close to their target.[108] In particular, IADS will cue antiair artillery toward an incoming aircraft flying at low altitude, which will be targeted by massed sustained artillery fire (barrage).[109] In other words, flying at low altitude can yield as much advantage as disadvantage, as this approach puts a MALE UAV within the reach of low-altitude engagement systems.

Fifth, flying at low altitude does not necessarily permit MALE UAVs to approach their target given that the missiles they typically carry have a relatively limited range. One of the most well-known aircraft designed to evade radar detection by flying at a low altitude was the B-1 Lancer, active in the latter phase of the Cold War.[110] The B-1, however, carried missiles that exceeded significantly the range of detection of Soviet radars.[111] This is not the case for MALE UAVs, whose missiles have a range of approximatively

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[104] Merrill I. Skolnik, "Fluttar DEW-Line Gap-Filler," in *Advances in Bistatic Radar*, ed. Nicholas J. Willis and Hugh D. Griffiths (Raleigh, NC: SciTech, 2007), 35–46.

[105] Zinger and Krill, "Mountain Top," 511–19; Lee O. Upton and Lewis A. Thurman, "Radars for the Detection and Tracking of Cruise Missiles," *Lincoln Laboratory Journal* 12, no. 2 (2000): 355–66.

[106] Carlo Kopp, "NKMZ 40V6M/40V6MD/40V6MT Universal Mobile Mast," Air Power Australia Technical Report APA-TR-2009-0504 (June 2011), http://www.ausairpower.net/APA-40V6M-Mast-System.html.

[107] *National Cruise Missile Defense*, 21–31.

[108] John Stillion and David T. Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks: Technology, Scenarios, and U.S. Air Force Responses* (Santa Monica, CA: RAND Corp., 1999), 45.

[109] *Electronic Warfare Fundamentals*, 8.12–8.15.

[110] The B-1 Lancer was designed with this very goal in mind. Andrew F. Krepinevich and Barry D. Watts, The *Last Warrior: Andrew Marshall and the Shaping of Modern American Defense Strategy* (New York: Basic Books, 2015), 130–32.

[111] Congressional Budget Office, *B-1B Bomber and Options for Enhancements*, 89–90; "AGM-86B/C/D Missiles," US Air Force, 24 May 2010, https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104612/agm-86bcd-missiles/.

only 10 km.[112] This means that these drones will not necessarily be able to safely approach the designated target and engage it from distance by flying at low altitude, as they will be detected before being within firing range.[113]

Slow Speed and Detection

Does flying at slow speeds significantly reduce the range at which drones will be detected, so much so that enemy air defense systems will be less likely to intercept them (shift toward the offense) or very unlikely to intercept them (shift to offense dominance)? In this case as well, this argument overstates the novelty brought about by drones, exaggerates its advantages, understates its key limitations, and neglects its disadvantages.

Aerial vehicles can lower the probability of being detected by enemy air defense systems by flying at slow speeds.[114] Radar systems automatically filter out radar echoes that, with high probability, do not represent incoming threats: those from stationary targets (by definition, they cannot be incoming threats) and from slow-moving targets (since they are unlikely to be incoming threats, and more likely either commercial vehicles like trains or motorbikes detected by airborne look-down radars, or birds detected by ground-based look-up radars).[115] By filtering out such radar returns, the radar operator will not be distracted by a multiplicity of false alarms, and the radar tracker will not be overwhelmed by a large number of potential targets.[116] Enemy forces can exploit such filtering functions of radar systems for an aerial attack: by flying at slow speeds, invading aircraft will lower the probability of detection (or postpone the time of detection). Yet such a tactic has limits and poses some risks.[117]

First of all, slow-speed flight is not a new capability drones introduced, which means that drones do not shift the ODB toward the offense compared to existing aerospace technologies. Plenty of aircraft can fly at slow speeds, including subsonic aircraft such as the A-10 Warthog and the Embraer EMB 314 Super Tucano, as well as supersonic jet fighters, whose slowest speed (that is, stall speed) is similar to the cruise speed of MALE UAVs (200 mph/330 kmph).[118]

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[112] The range of the Hellfire missile mounted on the American Reaper is between 8 and 11 km.

[113] This is particularly true when we consider that to intercept incoming enemy UAVs, a country can rely on ground-based air defense systems as well as on jet fighters that fly 3–4 times faster than MALE UAVs.

[114] Stimson, *Introduction to Airborne Radar*, 10, 317.

[115] William W. Shrader and Vilhelm Gregers-Hansen, "MTI Radar," in *Radar Handbook*, ed. Merrill I. Skolnik, 3rd ed. (New York: McGraw-Hill, 2008), 2.1–2.5.

[116] Stillion and Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, 16.

[117] The American Reaper has a cruising speed of about 300 km/h (190 mph) and a top speed of 450 km/h (300 mph).

[118] David R. Jacques and Dennis D. Strouble, *A-10 Thunderbolt II (Warthog) Systems Engineering Case Study* (Wright-Patterson Air Force Base, OH: Air Force Center for Systems Engineering (AFIT/SY), 2010), https://www.lboro.ac.uk/media/wwwlboroacuk/content/systems-net/downloads/pdfs/A-10%20Thunderbolt%20II%20(Warthog)%20SYSTEMS%20ENGINEERING%20CASE%20STUDY.pdf.

Second, slow-moving targets pose more of a problem for airborne radars oriented toward the ground than for ground-based radar oriented toward the sky.[119] By looking at the ground, airborne radar receive countless unwanted radar returns (clutter) that can mask the small RCS of an incoming aircraft.[120] Historically, however, this problem has been reduced by pointing airborne radar at a downward angle that illuminates the horizon rather than the ground, so as to minimize the ground clutter reflection and to increase the chances of detecting an incoming threat.[121]

Third, modern radars and signal processing can address the threat of slow-moving targets. Radar takes advantage of the change in frequency of an electromagnetic wave that results from encountering a moving object (called the Doppler effect) to distinguish incoming threats from clutter (birds, buildings, trees, etc.).[122] Slow speed, however, poses problems because of filtering functions. Therefore, these problems can be addressed by changing such filtering and through more advanced signal and data processing.[123] This used to be a solution only for ground-based radar, whose advanced computational capabilities could deal with a very large number of potential targets: already in the 1990s, they could automatically detect and track hundreds or thousands of incoming threats.[124] Conversely, airborne radars used to have more limited computational capabilities, which restricted the number of "radar tracks" they could hold concurrently, and hence changing the filtering function was not really an option.[125] Over the past twenty years, however, improvements in computing have largely addressed this problem, and today's airborne radars can also simultaneously track hundreds of targets.[126] Moreover, by collecting and storing the clutter of a given area, modern radar systems can more accurately disentangle a known unwanted return from an unknown but potentially relevant return in future iterations.[127] Along the same lines, over the past fifteen years, advances in data storage and data analytics have brought about new capabilities that allow such systems to more accurately and more rapidly process a much larger volume of information to better discriminate

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[119] Clark, "Early Advances in Radar Technology for Aircraft Detection"; Marshall Greenspan, "The Evolutionary Development of Airborne Surface Moving Target Detection," in *2015 IEEE Radar Conference: Proceedings* (Piscataway, NJ: IEEE, 2015), 1412–16.

[120] Lynch, *Introduction to RF Stealth*, 221.

[121] Stillion and Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, xx.

[122] Stimson, *Introduction to Airborne Radar*, 10–11.

[123] Ibid., 318–22; Stillion and Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, 46–47.

[124] Stillion and Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, xiii–xiv; Mac E. Van Valkenburg, *Reference Data for Engineers: Radio, Electronics, Computer and Communications* (Hoboken, NJ: Elsevier, 2001), 36.4, 36.22.

[125] Stillion and Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, 16–17.

[126] Stimson et al., *Stimson's Introduction to Airborne Radar*, 44–45.

[127] Lynch, *Introduction to RF Stealth*, 209–21; Kristin F. Bing et al., "Automatic Target Recognition," in *Principles of Modern Radar*, vol. 2, *Advanced Techniques*, ed. William L. Melvin and James A. Scheer (Edison, NJ: SciTech, 2013), 631–68.

slow-moving targets from clutter, so much so that even extremely slow objects such as cars, small boats, and even people can be detected.[128]

Fourth, slow speed provides as much advantage as disadvantage, as it exposes drones to the variety of existing and unsophisticated air defense systems such as small arms, machine guns, antiair artillery, and MANPADs, in addition to the possibility of being engaged by patrolling aircraft that can fly three to five times as fast as military drones.[129]

Next-Generation Drones against Next-Generation Air Defenses

In this section we investigate whether next-generation drones will shift the ODB in the future. We identify some technological trends that the debate on emerging technology has ignored, and that are already strengthening air defense. Although it is impossible to predict the net effect of offense- and defense-enhancing technological change, our findings raise questions about the accepted wisdom. Next-generation drones might very well shift the ODB in the end, but, as of now, such an outcome cannot be taken for granted.

Stealth Drones and Air Defense Systems

Will the application of stealth technology to next-generation drones shift the ODB toward the offense or to offense dominance? Though this argument is intuitive at face value, it ignores concomitant improvements in air defense systems that have already reduced the advantage of stealth—including in data collection (sensor acuity and multisensor connectivity), data storage (big data), and data analytics (for example, machine learning). This does not mean we are moving toward an era of air defense dominance. It means that by ignoring trends strengthening the defense side of the equation, existing debates have possibly reached premature conclusions.

Stealth technology aims at reducing the RCS of an aircraft, with the goal of minimizing the probability of detection and/or interception, and hence maximizing the chance of success of a military mission in a hostile environment.[130] For this reason, stealth technology does not need to avert detection altogether, but it can more simply aim at breaking the “kill-chain” in the enemy’s air defense system—that is, the sequence of detection, identification, tracking, engagement, and damage/destruction. One way to

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[128] William L. Melvin, “Adaptive Moving Target Indication,” in Willis and Griffith, *Advances in Bistatic Radar*, 433; Michael S. Davis, “MIMO Radar,” in Melvin and Scheer, *Principles of Modern Radar* 2:140–41; Mark A. Richards, “Interferometric SAR and Coherent Exploitation,” in Melvin and Scheer, *Principles of Modern Radar* 2:389–92.

[129] Gary Schaub Jr., Kristian Søby Kristensen, and Flemming Pradhan-Blach, *Long Time Coming: Developing and Integrating UAVs into the American, British, French, and Danish Armed Forces* (Copenhagen: Centre for Military Studies, 2014), 15–17.

[130] Lynch, *RF Stealth*, 1–60; Grant, *Radar Game*, 29–36.

accomplish this goal is to postpone detection by enemy surveillance radar, so that there is not enough time for the air defense system to react and engage the incoming aircraft.[131] Another way to break the enemy "kill-chain" is to limit the capacity of enemy fire-control radar to track one's aircraft—a critical step for launching surface-to-air or air-to-air missiles at an incoming target.[132] It is true that the application of stealth technology could make drones less detectable and/or trackable to current-generation air defense systems, but we cannot take for granted that stealth will be effective against next-generation air defense systems as well.

First, expectations about stealth drones ignore developments in radar technology over the past twenty years that have already degraded, and promise to further degrade, the advantage of stealth.[133] To start, progress in materials such as semiconductors (first gallium arsenide, then gallium nitride, and, in the near future, gallium oxide) has allowed for the development of more accurate and more powerful sensors.[134] Moreover, the growing capacity of collecting, storing, retrieving, and processing environmental and operational data produces lower standard errors, which enhances statistical estimates, and thus increases, everything else being equal, the probability of detection.[135] Additionally, computer-aided detection, automatic target detection, digital signal processing, and machine learning lower the signal-to-noise threshold for detecting enemy aircraft—that is, by extracting weaker signals, identifying patterns that once could not be identified, suppressing unwanted returns (clutter) more effectively, and correlating a larger stock of more accurate radar returns with received signals.[136] Last but definitively not least, the application of artificial intelligence and more advanced communications to radar systems have permitted the development of multistatic radars that can degrade and possibly defeat stealth technology.[137] A key feature of stealth technology is the shaping of an

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[131] Stealth technology does not make an aircraft invisible, but it decreases significantly the range at which it can be detected. When the range of detection is very limited, air defense systems might still be able to detect an incoming aircraft, but it might be too late to track or engage it. John Shaeffer, *Understanding Stealth* (Marietta, GA: Marietta Scientific, n.d.), 1–4.

[132] Lynch, *Introduction to RF Stealth*, 195–98.

[133] Carlo Kopp, "Evolving Technological Strategy in Advanced Air Defense Systems," *Joint Force Quarterly*, no. 57 (Spring 2010): 86–93.

[134] Kingsley and Quegan, *Understanding Radar Systems*, 310–11; Robert J. Trew et al., "Microwave AlGaN/GaN HFETs," *IEEE Microwave Magazine* 6, no. 1 (March 2005): 56–66; *Electronic Warfare and Radar Systems: Engineering Handbook*, 4th ed. (Point Mugu, CA: Naval Air Warfare Center Weapons Division, 2013), 3–7.1; Gregg H. Jessen, "Gallium Oxide: The Supercharged Semiconductor," *IEEE Spectrum*, 24 March 2021.

[135] Lynch, *Introduction to RF Stealth*, 195–98; Sukharevsky, *Electromagnetic Wave Scattering*, xix, 91.

[136] Arye Nehorai, Mark R. Bell, John Benedetto, Robert Calderbank, Danilo Erricolo, Navin Khaneja, William Moran, Darryl Morrell, Antonia Papandreou-Suppappola, Harry Schmitt, et al., "MURI: Adaptive Waveform Design for Full Spectral Dominance (2005–2010)," AFOSR FA9550-05-1-0443, final report (2011), https://apps.dtic.mil/sti/pdfs/ADA565420.pdf.

[137] Victor S. Chernyak, *Fundamentals of Multisite Radar Systems: Multistatic Radars and Multiradar Systems* (Amsterdam: Overseas Publisher Association, 1998); Ngoc Hung Nguyen and Kutluyil Doğançay, *Signal Processing for Multistatic Radar Systems: Adaptive Waveform Selection, Optimal Geometries and Pseudolinear Tracking Algorithms* (London: Academic Press 2020).

aircraft intended to deflect radar pulses away, rather than reflecting them back toward the emitting antenna.[138] In contrast to traditional radars—called monostatic because they employ one radar emitter and one radar receiver that are colocated—multistatic radars employ one or more (active) radar emitters and multiple spatially distributed (passive) radar receivers.[139] This means that multistatic radars can receive radar pulses deflected away by a stealth aircraft that monostatic radars would miss.[140] It goes without saying that the deployment of multistatic radars will not necessarily end the advantages of stealth technology. It means that, in the future, reducing the probability of detection will be even more demanding for aircraft designers, and that existing stealth technology will likely be insufficient.[141]

Second, stealth technology is inherently incompatible with two key advantages of military drones: their technological unsophistication and their low cost, which in turn have promoted their proliferation. Stealth technology means reducing radar reflections by several orders of magnitude, which is a technologically demanding and unforgiving effort, in that minor mistakes or imperfections can defeat the whole purpose.[142] This is why reductions in observability to enemy sensors requires extensive work at the design, development, production, and maintenance stages, in that personnel with extensive experience conduct very specialized tasks with sophisticated machinery and instruments at highly specific production and testing facilities.[143] Altogether, stealth entails sacrificing technological unsophistication, which leads to the escalation of the unit cost of military drones.[144] The implication is that very few countries will be able to pursue this approach.

Third, some might wonder whether producers of next-generation military drones could find a middle way and opt for technological solutions aimed at reducing observability to enemy sensors that are less demanding and cost effective, such as the application of radar-absorbing materials (RAMs). RAMs have electric properties such that when illuminated by enemy radar, they absorb part of the incoming electromagnetic wave; hence they

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[138] For a graphical illustration, see, for example, Lynch, *Introduction to RF Stealth*, 6; Schaeffer, *Understanding Stealth*, 8.

[139] For a discussion, see E. Hanle, "Survey of Bistatic and Multistatic Radar," *IEE Proceedings F: Communications, Radar, and Signal Processing* 133, no. 7 (December 1986): 587–95; J. I. Glaser, "Fifty Years of Bistatic and Multistatic Radar," *IEEE Proceedings F: Communications, Radar, and Signal Processing* 133, no. 7 (December 1986): 596–603.

[140] Moreover, the geometry of multistatic radars also enhances the RCS of stealth aircraft. Nathanson et al. *Radar Design Principles*, 211–14.

[141] This said, other than detecting, multistatic radar will have also to track, identify, and correctly geolocate stealth drones.

[142] Alan Brown in Rich and Janos, *Skunk Works*, 81. In the future, the pursuit of stealth will be even more demanding. Filippo Neri, *Introduction to Electronic Defense Systems*, 3rd ed. (London: Artech House, 2018), 28.

[143] Alfred Price, *War in the Fourth Dimension: US Electronic Warfare, from the Vietnam War to the Present* (London: Greenhill Books, 2001), 197.

[144] Rich and Janos, *Skunk Works*, 325.

attenuate the energy reflected by the aircraft, and thus reduce the range of detection and/or tracking.[145] This possibility exists, but it has limitations and constraints. To start, RAMs play, in general, only a small part in RCS reductions—for instance, at given frequencies the primary determinant of the RCS is the shape of a vehicle.[146] Moreover, the radar echo reduction resulting from the employment of RAMs varies significantly with radar frequency, polarization, and angle of incidence (azimuth and elevation). Thus it does not systematically reduce the chance of detection, tracking, and engagement by enemy air defenses, but it reduces them only under some specific conditions.[147] One might point out that a drone producer will likely employ RAMs that are particularly effective for fire-control radars—that is, those tasked with tracking and engaging an incoming threats (2.5–3.75 cm wavelength). This objection is sound, but it neglects that RAMs do not shield prominent features that scatter incoming radar waves—the undercarriage missiles, the E/O camera, and the engine of MALE UAVs. As a result, the savvy employment of RAMs will not reduce, either systematically or significantly, the vulnerability of MALE UAVs to detection and engagement.[148] Additionally, the effectiveness of RAMs in the future will be a function of advances in radar systems. For instance, to absorb incoming radar waves, composite carbon fibers must have a peculiar internal structure—that is, they need to display an internal angle that is attuned to the polarization of the incoming radar wave.[149] This approach, however, is very effective only for vertical or horizontal polarization.[150] Modern air defense systems such as the Russian S-400 employ circular polarization to reduce this very problem.[151] Finally, as discussed, UAVs can be engaged also by air defense systems that do not need radar tracking, such as antiair artillery barrage that rely on infrared sensors and augmented visual sight as well as MANPADs that depend on infrared sensors or laser.[152] This means that RAMs' effectiveness is limited to only radar-guided systems.

Fourth, one might wonder whether endowing military drones with an electronic warfare (EW) suite could be an effective and efficient solution to enhance their survivability against next-generation air defense systems, compared to stealth through shaping and materials. EW offers several

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[145] Adrian P. Mouritz, *Introduction to Aerospace Materials* (Philadelphia: Woodhead, 2012), 296–98; Hema Singh et al., *Fundamentals of EM Design of Radar Absorbing Structures (RAS)* (Singapore: Springer, 2018).

[146] Dan Katz, "The 'Magic' behind Radar-Absorbing Materials for Stealthy Aircraft," *Aviation Week & Space Technology*, 28 October 2016.

[147] Singh et al., *Fundamentals of EM Design of Radar Absorbing Structures*, 19–26.

[148] Elliot J. Riley, Erik H. Lenzing, and Ram M. Narayanan, "Characterization of Radar Cross Section of Carbon Fiber Composite Materials," in *Radar Sensor Technology XIX; and Active and Passive Signatures VI, SPIE Proceedings* vol. 9461, ed. G. Charmaine Gilbreath, Chadwick Todd Hawley, Kenneth I. Ranney, and Armin Doerry (Bellingham, WA: SPIE Press, 2015).

[149] Ibid.

[150] Ibid.

[151] Interview with defense electronics engineer, 20 September 2020.

[152] Stillion and Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, 45.

advantages, but it also imposes key technological challenges and an escalation of costs. The use of radar during World War II led to the employment of electronic countermeasures aimed at blinding or deceiving enemy radars.[153] Over the past eighty years, EW has come to play a central role in modern military operations.[154] Yet, to be effective, electronic countermeasures must be more advanced than the electronic counter-countermeasures of the enemy's air defense systems. This entails a never-ending technological race.[155] Moreover, this race will lead to the escalation of unit costs, which will increasingly converge toward that of traditional military aircraft.[156]

Finally, effective stealth capabilities are inherently incompatible with proliferation. Stealth implies surprise. Surprise requires that enemy air defense systems do not have any information about the incoming platform—that is, its unique radar return, the structure and composition of its RAMs, or how its electronic countermeasures work. If next-generation drones were to proliferate, as happened over the past decade with the American Reaper, the Chinese Wing-Loong II, or the Turkish TB2, their stealth capabilities would inevitably suffer significantly, as multiple countries would be able to gain access to these technologies, and analyze them. This information would then improve the capacity of air defense systems to defeat foreign stealth drones.[157] This is why the United States has not sold its forefront stealth aircraft such as the F-117, the F-22, and the B-2 to any ally, and why it excluded Turkey from the F-35 Joint Strike Fighter/Lightning II program after the latter purchased the very air defense system the F-35 is supposed to defeat, the Russian-made S-400.[158]

Saturation and Air Defense Systems

Will the employment of large numbers of drones shift the ODB toward the offense or to offense dominance? This argument is intuitive at face value, but it neglects some key challenges that are already present and that might

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[153] Michael Russell Rip and James M. Hasik, *The Precision Revolution: GPS and the Future of Aerial Warfare* (Annapolis, MD: Naval Institute Press, 2002), 19–48.

[154] Mario de Arcangelis, *Electronic Warfare: From the Battle of Tsushima to the Falklands and Lebanon Conflicts* (Dorset: Blandford Press, 1985).

[155] Alfonso Farina, "Electronic Counter-Countermeasures," in *Radar Handbook*, ed. Merrill I. Skolnik, 3rd ed. (New York: McGraw-Hill, 2008), 24.1–24.58.

[156] *The UK Approach to Unmanned Aircraft Systems*, Joint Doctrine Note 2/22 (Shrivenham, UK: Development, Concepts and Doctrines Centre, Ministry of Defence, 30 March 2011), 1–2.

[157] Guy Ardon, Or Simko, and Akiva Novoselsky, "Aerial Radar Target Classification Using Artificial Neural Networks," in *Proceedings of the 9th International Conference on Pattern Recognition Applications and Methods (ICPRAM 2020)*, ed. Maria De Marsico, Gabriella Sanniti di Baja, and Ana Fred (Setúbal, Portugal: Science and Technology Publications, 2020), 136–41. For the same dynamics, but in the cyber domain, see Max Smeets, "Cyber Arms Transfer: Meaning, Limits, and Implications," *Security Studies* 31, no. 1 (January–March 2022): 65–91.

[158] Selim Sazak, "Why Did Turkey Buy the Russian S-400?" *Monkey Cage* (blog), 17 July 2019.

become more marked in the near future. Most prominently, mass can be employed on both sides of a conflict, as trench warfare in World War I shows: if military drones are vulnerable to air defense systems, their use will then lead to a bloodless bloodbath of robots. In this section, we discuss some of the key challenges for future drone saturation tactics. To be clear, we do not claim that the ODB in the air is going to shift to a future era of air defense dominance. Mass might very well yield an offensive advantage. We claim that by neglecting trends strengthening the defense, existing debates have presented a biased and incomplete picture.

Saturation tactics rely on numerical superiority to overwhelm enemy air defenses. This approach is effective because, generally, air defense systems have a limited stock of missiles and munitions to expend and because they can engage only a limited number of targets at any one time. This means that, although air defense systems will be able to shoot down some incoming aircraft, others will inevitably get through. Saturation tactics, however, do not ensure that the ODB will shift toward the offense or to an era of air offense dominance.

First, IADS rely on a virtually unlimited supply of cyber capabilities, EW jamming, high-power microwave shock systems, and soon, according to some accounts, direct-energy weapons.[159] If next-generation UAVs will still be piloted through a line-of-sight radio communication, these communications could be jammed by enemy EW capabilities.[160] Furthermore, drones are vulnerable to cyberattacks and hacking, through which air defense systems can try to seize control of incoming enemy drones.[161] Moreover, air defense systems can rely on microwave shock systems and direct-energy weapons. These systems have two limitations: they require large amounts of energy to operate efficiently, and their laser beam capability (to damage and destroy targets) is limited by airborne dust and other factors.[162] Thus, these weapons require large, heavy batteries to operate, which could reduce the mobility and hence the employment of systems that carry them.[163] However, countries such as United States, Russia, and China are testing and developing laser weapons equipped on ships, ground vehicles, fighter jets, and even on UAVs in order to guarantee in the near future an all-domains force protection from attacks of drones.[164]

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[159] Mark Gunzinger, Carl Rehberg, Jacob Cohn, Timothy A. Walton, and Lukas Autenried, *An Air Force for an Era of Great Power Competition* (Washington, DC: CSBA, 2019), 48.

[160] Schaub et al., *Long Time Coming*, 15–17.

[161] Kreuzer, *Drones and the Future of Air Warfare*, 165.

[162] Vladimir P. Lukin and Boris V. Fortes, *Adaptive Beaming and Imaging in the Turbulent Atmosphere*, trans. A. B. Malikova (Bellingham, WA: SPIE Press, 2002), 107.

[163] Mark Gunzinger with Chris Dougherty, *Changing the Game: The Promise of Directed-Energy Weapons* (Washington, DC: CSBA, 2012), 51–52.

[164] Mandy Mayfield, "Air Force Wants Lasers on Fighter Jets by 2025," *National Defense*, 9 November 2020, https://www.nationaldefensemagazine.org/articles/2020/11/9/air-force-wants-lasers-on-fighter-jets-by-2025.

Second, traditional air defense systems are already capable of engaging a large number of incoming targets. Consider the air defense for a critical node or infrastructure by SHORAD systems such as Skyshield by the German manufacturer Rheinmetall or Pantsir S-1 by the Russian KBP Instrument Design Bureau. An antiair artillery cannon like that of Pantsir S-1 can shoot up to 750 rounds before reloading (at 2,500 rounds per minute).[165] Given that limited structural damage can be critical for MALE UAVs, antiair artillery can be very efficient. The question, then, is not really about mass, but about accuracy and efficiency: How many shots will hit the target, and how many hits are needed to structurally damage it? Moreover, over the past few years, air defense producers have come up with innovations intended to enhance the probability of hitting small targets. For example, the Skyshield can fire Advanced High Efficiency and Destruction (AHEAD) ammunition that, at a programmable time, detonate in front of a target, ejecting a cloud of "spin-stabilized cylindrical tungsten sub-projectiles" that maximize the chance of enemy interception and destruction.[166] A Skyshield comes with either one or two gun turrets, and each can fire 228 rounds of AHEAD ammunition.[167] Moreover, systems such as Skyshield and Pantsir can also fire up to 12 inexpensive surface-to-air missiles.[168] Given that MALE UAVs do not have any self-defense mechanism to deceive incoming missiles (such as chaff or flares), and given that their limited maneuverability constrains their ability to evade an incoming missile, the chances of survival when tracked by an engagement radar are reasonably low. This means that, even under conservative expectations, a Skyshield or Pantsir could shoot down a significant number of incoming UAVs.

Third, the very same technological dynamics strengthening the offense also strengthen the defense. Remote control, for example, permits to geographically distribute engagement systems (whether antiair artillery or surface-to-air missiles), which makes them more independent from the location of acquisition radars and hence less vulnerable to enemy suppression, while ensuring higher redundancy of the whole system, and providing more comprehensive air defense coverage. Along the same lines, remote control and automation have led to the increasing employment of military

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[165] "Pantsyr S1 Close Range Air Defence System," Army-technology.com, https://www.army-technology.com/projects/pantsyr/.

[166] "Rheinmetall Airburst Technology: Superior Firepower from Small Arms to Main Battle Tanks," Rheinmetall Defense press release, 5 September 2017, https://www.rheinmetall-defence.com/media/editor_media/rm_defence/publicrelations/pressemitteilungen/2017/2017-09-05_Rheinmetall_MSPO_AirBurst_en.pdf.

[167] "Oerlikon Skyshield Ground-Based Short-Range Air Defense System, *Army Recognition*, 17 February 2018, https://www.armyrecognition.com/germany_german_army_artillery_vehicles_systems_uk/skyshield_oerlikon_ground-based_short_range_air_defense_system_cannon_missile_technical_data_sheet.html.

[168] Ben Brimelow, "Russia's Newest Anti-air Defenses Are in Syria—and the US Should Be Worried," *Business Insider*, 11 April 2018, https://www.businessinsider.com/pantsir-s1-makes-russian-air-defenses-stronger-2018-2?IR=T.

drones for air patrol and early warning, in that these systems provide persistent surveillance and are not vulnerable to the limitations of manned aircraft (such as exhaustion, fatigue, and limited range).[169] The cooperation between manned and unmanned vehicles could strengthen the defense's capabilities to detect, track, and eventually engage incoming threats.[170] Finally, the further development and application of artificial intelligence and quantum computing in radar technology could enhance the capability to predict a target's route and consequently its aim.[171] To go even one step farther, we could hypothesize that this information can be processed and shared in real time to other autonomous combat systems able to fly at the target and destroy it—creating a sort of aerial minefield.

Fourth, to maintain their low cost and technological unsophistication the drones employed with swarming tactics will be subjected to hard tradeoffs, such as between range and payload.[172] Thus, hardening critical nodes, such as those in IADS, and endowing them with point defenses could be sufficient to prevent saturation attacks from having operational effects.

Recent Conflicts and Policy Implications

With this article, we have contributed to the debate on emerging technologies by investigating the widely accepted assumption that armed MALE and HALE drones yield or will yield an offensive advantage. Our findings question existing understandings. Regarding current-generation drones, we find that small size, slow speed, and low flight altitude are not sufficient to defeat current-generation air defense systems. For next-generation drones, we have shed light on defense-enhancing technological change that the debate on emerging technologies has largely ignored. Next-generation drones might very well shift the ODB in the end. But, as our analysis points out, it is not possible to reach this conclusion by looking only at one side of the equation—how technological change is going to strengthen the offense. Looking at how it is going to strengthen the defense as well is critical.

Evidence from the employment of military drones over the past two decades substantiates our findings. On 20 June 2019 a surface-to-air missile operated by Iran shot down a US drone over the Strait of Hormuz.[173] The

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[169] *National Cruise Missile Defense*, 21–38, https://www.cbo.gov/system/files/2021-02/56950-CMD.pdf; Mahnken, Sharp, and Kim, *Deterrence by Detection*.

[170] Gunzinger et al., *Air Force for an Era of Great Power Competition*, 84–88.

[171] Lynch, *Introduction to RF Stealth*, 201–22; Sukharevsky, *Electromagnetic Wave Scattering*, xix, 91.

[172] Gettinger, *The Drone Databook*, v; Shmuel Shmuel, "The Coming Swarm Might Be Dead on Arrival," *War on the Rocks*, 10 September 2018, https://warontherocks.com/2018/09/the-coming-swarm-might-be-dead-on-arrival/; Sebastian Sprenger, "Britain's Royal Air Force Chief Says Drone Swarms Ready to Crack Enemy Defenses," *Defense News*, 14 July 2022.

[173] "Strait of Hormuz: US Confirms Drone Shot Down by Iran," *BBC*, 20 June 2019, https://www.bbc.com/news/world-middle-east-48700965.

drone, an RQ-4A Global Hawk BAMS-D, comes with a price tag of over $170 million USD.[174] Its downing generated worldwide media attention, leading some to speculate that the vulnerability of US drones would have negative repercussions for its arms sales abroad, whereas others wondered why such an expensive drone could be so easily shot down. In fact, this episode was a stark reminder that MALE and HALE drones are inherently vulnerable to air defense systems, and that the use of drones for counterinsurgency operations during the global "War on Terror" has been possible because rebels generally lack capable air defenses. Yet, over the past two decades, even rebels have downed MALE UAVs via rifle shots, off-the-shelf software, antiair artillery, and other means.[175] In 2020, the downing of US UAVs became so frequent that the US Air Force had to devise new tactics and countermeasures.[176]

The vulnerability of military drones is even more evident when we look at their employment over countries with more advanced air defense systems.[177] In 2001, Iraq shot down a US Predator drone with surface-to-air missiles.[178] In 2011, Iran downed a US RQ-170 Sentinel allegedly through cyber hacking.[179] The Libya civil war offers an even more complete picture. The two factions fighting for control of the country have relied extensively on armed drones, which led some to conclude that a new era of warfare was beginning.[180] In the first part of 2019, one of these factions achieved air superiority over the western coastal area of the country and could operate its Chinese-made drones (Wing Loong II) with relative impunity.[181] Though such an epilogue suggests that drones have an offensive advantage at face value, under closer scrutiny, it does not. Such a

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[174] Tara Law, "Iran Shot Down a $176 Million U.S. Drone. Here's What to Know about the RQ-4 Global Hawk," *TIME*, 21 June 2019, https://time.com/5611222/rq-4-global-hawk-iran-shot-down/.

[175] Siobhan Gorman, Yochi J. Dreazen, and August Cole, "Insurgents Hack U.S: Drones," *Wall Street Journal*, 17 December 2009, https://www.wsj.com/articles/SB126102247889095011; Shawn Snow, "US MQ-9 Drone Shot Down in Yemen," *Military Times*, 2 October 2017, https://www.militarytimes.com/flashpoints/2017/10/02/us-mq-9-drone-shot-down-in-yemen/; "Downed Drone in Yemen's Capital Kills Three," *Al Jazeera*, 24 May 2022, https://www.aljazeera.com/news/2022/5/24/downed-drone-in-yemens-capital-kills-locals.

[176] Garrett Reim, "Record Number of UAV Shoot Downs Prompt New USAF Tactics and Countermeasure Pod," *FlightGlobal*, 30 June 2020, https://www.flightglobal.com/military-uavs/record-number-of-uav-shoot-downs-prompt-new-usaf-tactics-and-countermeasure-pod/138908.article#toggle.

[177] For an investigation, see, for example, Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti, and Ivan Zaccagnini, "Why Drones Have Not Revolutionized War: The Enduring Hider-Finder Competition in Air Warfare," *International Security* 46, no. 4 (Spring 2022): 130–71; Heiko Borchert, Torben Schütz, and Joseph Verbovszky, *Beware the Hype: What Military Conflicts in Ukraine, Syria, Libya, and Nagorno-Karabakh (Don't) Tell Us about the Future of War* (Hamburg, Germany: Defense AI Observatory, 2021).

[178] "U.S. Spy Drone Missing over Iraq," *CNN*, 11 September 2001, http://edition.cnn.com/2001/WORLD/meast/09/11/iraq.shootdown/.

[179] "Iran Shows Film of Captured US Drone," *BBC*, 8 December 2011, https://www.bbc.com/news/world-middle-east-16098562.

[180] Nathan Vest and Colin P. Clarke, "Is the Conflict in Libya a Preview of the Future of Warfare?" *Defense One*, 2 June 2020, https://www.defenseone.com/ideas/2020/06/conflict-libya-preview-future-warfare/165807/.

[181] Jason Pack and Wolfgang Pusztai, *Turning the Tide: How Turkey Won the War for Tripoli* (Washington, DC: Middle East Institute, November 2020), 5, https://www.mei.edu/sites/default/files/2020-11/Turning%20the%20Tide%20-%20How%20Turkey%20Won%20the%20War%20for%20Tripoli.pdf;

drone campaign was in fact possible because of the other faction's limited air defense capabilities—which possessed only antiaircraft artillery and MANPADs. In November 2019, however, Turkey took advantage of a temporary ceasefire to deploy two HAWK II surface-to-air missile batteries and radar systems in support of the weaker faction.[182] With these capabilities, the Chinese drones were quickly shot down.[183]

Evidence from the 2020 Nagorno-Karabakh war between Azerbaijan and Armenia provides further evidence in this direction. Analysts and observers called Azeri employment of Turkish drones in this conflict a "game changer."[184] At face value this claim seems correct, as Turkish TB2 drones destroyed Armenian air defense systems, and then went on to strike Armenian ground forces. With closer scrutiny, however, the Turkish drones' success was not a product of their capabilities, but of the obsolescence of Armenian air defense systems and of the ability of Turkish jamming systems that blinded Armenian radars, among others.[185] In fact, when Armenia deployed more advanced air defense systems, it managed to bring the Azeri drone campaign to an end—these defensive systems, however, were deployed too late in the conflict to have a real effect.[186]

During the 2022 Russian invasion of Ukraine, both sides have made extensive use of drones. Some saw Turkish TB2s used by Ukraine drones as a "game changer."[187] Others, however, downplayed their effectiveness.[188] At the time of writing the conflict is still ongoing, and it is not possible to derive any definitive conclusion yet. What we know, however, is consistent with our article's findings. During the first part of the war, Russia shot down 8 to 9 TB2s out of the 20 that Ukraine allegedly had in its inventory.[189] Moreover, since Russia redirected its war effort toward the Donbass region, where Russia allegedly has effective air defenses, the media has not reported any significant military accomplishment by TB2s. In fact, according to a Ukrainian air force

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[182] Feridun Taşdan, "Turkish EW Systems: The Unseen Force behind Recent Turkish Drone Successes," *Turkey Defense* 15, no. 106 (May 2021), https://www.defenceturkey.com/en/content/turkish-ew-systems-the-unseen-force-behind-recent-turkish-drone-successes-4532; Ali Bakir, "Turkey's Electronic Warfare Capabilities: The Invisible Power behind Its UACVs," *RUSI*, 27 September 2021, https://rusi.org/explore-our-research/publications/commentary/turkeys-electronic-warfare-capabilities-invisible-power-behind-its-uacvs.

[183] Pack and Pusztai, *Turning the Tide*, 5.

[184] Arshaluys Mgdesyan, "Drones: A Game Changer in Nagorno-Karabakh," *Eurasia Review*, 2 November 2020, https://www.eurasiareview.com/02112020-drones-a-gamechanger-in-nagorno-karabakh/.

[185] Bakir, "Turkey's Electronic Warfare Capabilities."

[186] Shaan Shaikh and Wes Rumbaugh, "The Air and Missile War in Nagorno-Karabakh: Lessons for the Future of Strike and Defense," Center for Strategic and International Studies, 8 December 2020, https://www.csis.org/analysis/air-and-missile-war-nagorno-karabakh-lessons-future-strike-and-defense.

[187] Ed Cumming, "The Game-Changing Turkish Drones Tormenting the Russians," *Telegraph*, 16 May 2022, https://www.telegraph.co.uk/news/2022/05/16/turkish-drones-changed-game-ukraine-come-catchy-ditty/.

[188] Elmas Topcu, "How Useful Are Turkish-Made Drones Fighting in Ukraine?" *DW*, 3 March 2022, https://www.dw.com/en/how-useful-are-turkish-made-drones-fighting-in-ukraine/a-61035894.

[189] "List of Aircraft Losses during the 2022 Russian Invasion of Ukraine," *Oryx*, 20 March 2022, https://www.oryxspioenkop.com/2022/03/list-of-aircraft-losses-during-2022.html; Amberin Zaman, "Turkish Drones Boost Ukrainian Spirits amid Fears of Russian Invasion," *Al-Monitor*, 27 January 2022, https://www.al-monitor.com/originals/2022/01/turkish-drones-boost-ukrainian-spirits-amid-fears-russian-invasion.

pilot, TB2s "were very useful and important in the very first days [of the war], stopping those columns [of armored vehicles], but now that [the Russians]'ve built up good air defenses, they're almost useless."[190] This pilot then added that "it's very dangerous to use such expensive drones in our case, because of the enemy's air defense … It's not Afghanistan here."[191] Far from employing its drones to launch the counteroffensive in the Donbass, Ukraine has been asking for heavier types of equipment, including armored vehicles and long-range artillery.[192]

The vulnerability of military drones is evident also when employed in large numbers to saturate enemy air defenses. Consider instances from the Syrian civil war. Between 2018 and 2020, Russian-made air defenses like the Pantsir S-1 and S-400 disabled over 150 drones of different categories; in 2019 alone, Russia managed to neutralize around 60 multiple-drone-and-missile attacks against its Khmeimim air base.[193] In a similar fashion, Israeli airborne and ground-based air defense systems successfully intercepted and destroyed rockets and drones launched by the Palestinian organization Hamas.[194] We are not claiming, however, that MALE UAVs cannot penetrate an enemy's airspaces. We argue that doing it systematically against a country with IADS is extremely difficult. Some apparent successes do exist, such as the September 2019 drone and missile attack on the Aramco oil facilities in Saudi Arabia.[195] This case generated reactions echoing the debate on drones. According to some, this attack signaled that the era of expensive jet fighters was finally over, given the effectiveness of affordable drones.[196] Others argued that in the age of drone warfare, spending billions of dollars on air defenses like the MIM-104 Patriot is a waste of resources.[197] In fact, little is known about this attack, and these conclusions seem at least premature. To start, as explained above, ground-based air defense systems like the Patriot that Saudi Arabia employed to defend these oil facilities are not designed to detect low-flying targets at

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[190] Jack Detsch, "'It's Not Afghanistan': Ukrainian Pilots Push Back on U.S.-Provided Drones," *Foreign Policy*, 21 June 2022, https://foreignpolicy.com/2022/06/21/ukraine-us-drones-pushback/.

[191] Detsch, "'It's Not Afghanistan.'"

[192] "The West Needs to Send Ukraine More and Better Weapons," *Economist*, 23 April 2022.

[193] Ridvan Bari Urcosta, "The Revolution in Drone Warfare: The Lessons from the Idlib De-escalation Zone," *European, Middle Eastern and African Affairs* 2, no. 3 (Fall 2020): 51.

[194] Sameer Joshi, "Drone Swarms: The Next Evolution in Warfare," *Raksha Anirveda*, 8 February 2021, http://www.raksha-anirveda.com/drone-swarms-the-next-evolution-in-warfare/; Seth J. Frantzman, "Iron Dome Intercepts Drone during Combat for First Time, Says Israeli Military," *Defense News*, 17 May 2021, https://www.defensenews.com/unmanned/2021/05/17/iron-dome-intercepts-drone-during-combat-for-first-time-says-israeli-military/.

[195] Natasha Turak, "How Saudi Arabia Failed to Protect Itself from Drone and Missile Attacks Despite Billions Spent on Defense Systems," *CNBC*, 19 September 2019, https://www.cnbc.com/2019/09/19/how-saudi-arabia-failed-to-protect-itself-from-drones-missile-attacks.html.

[196] Martin Chulov, "Middle East Drones Signal End to Era of Fast Jet Air Supremacy, *Guardian*, 16 September 2019.

[197] Tim Lister, "The Billions Saudi Arabia Spends on Air Defenses May Be Wasted in the Age of Drone Warfare," *CNN*, 19 September 2019.

long distance.[198] Moreover, Saudi ground-based radars were allegedly turned in one specific direction instead of providing full 360 degree coverage—these drones might have used these gaps in radar coverage to reach their targets.[199] Additionally, to our knowledge, no analyst has investigated whether Saudi airborne radars—the only ones that could have detected the incoming drones at long range—were operative the night of the attack, and, if so, why they failed to detect the attack. In fact, after a year and a half, specialized media reported Saudi interest in aerostat radars to enhance its ability "to detect low-flying missiles and aircraft."[200]

Before concluding, we want to state explicitly that our analysis has inevitable limitations. We have looked only at armed drones employed as air-to-ground striking platforms; we have not explored other tactical settings or different drones serving other roles, such as decoys, remote jammers, and antiradiation missiles.[201] The interaction of newer technologies and newer tactics is an important topic that further research should investigate. At the same time, the implications of our analysis go beyond the specific case of drones. We have contributed to the broader debate on emerging technologies by showing that academics and analysts have focused almost exclusively on the offensive implications of emerging technologies while neglecting the defensive ones (such as those stemming from much more capable signal processing and multistatic radars). Last but not least, hopefully our article shows the promise of more interdisciplinary research for international relations and security studies scholars. In the 1990s and 2000s, scholars realized the need to borrow from other social sciences, most prominently economics, psychology, and sociology, to better understand world politics. As we move to an age of accelerating technological change, and with technology playing an increasingly pervasive role in society, our discipline will need to go beyond other social sciences and start borrowing from engineering disciplines and the natural sciences. This is a necessary condition for understanding how technical developments interact with and affect political decisions and international outcomes. Otherwise, contributing to policy debates will become increasingly more difficult. The sooner international relations and security studies scholars embrace this change, the better for the discipline as a whole.

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[198] Sébastien Roblin, "Why U.S. Patriot Missiles Failed to Stop Drones and Cruise Missiles Attacking Saudi Oil Sites," *NBC News*, 23 September 2019.

[199] Michael Safi and Julian Borger, "How Did Oil Attack Breach Saudi Defences and What Will Happen Next?" *Guardian*, 19 September 2019.

[200] Jeremy Binnie, "US Looking for Aerostat Air-Defence Radars for Saudi Arabia," *Janes*, 19 January 2021.

[201] For loitering munitions, see Mark Voskuijl, "Performance Analysis and Design of Loitering Munitions: A Comprehensive Technical Survey of Recent Developments," *Defence Technology* 18, no. 3 (March 2022): 325–43.

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