ADDITIONAL MATERIAL
FOR
WILL THE DRONE ALWAYS GET THROUGH?

This document contains additional explanations and sources in support of the analysis presented in the article "Will the Drone Always Get Through?," forthcoming in Security Studies. It is organized numerically, with each footnote corresponding to the one in the main manuscript.

Footnote 2: See also Eleni Ekmektsioglou, "Hypersonic Weapons and Escalation Control in East Asia," *Strategic Studies Quarterly* 9 (2015), pp. 43-68, https://jstor.org/stable/26271074; pp. 147-169; James S. Johnson, "Delegating Strategic Decision-Making to Machines: Dr. Strangelove Redux?," *Journal of Strategic Studies* (forthcoming); Austin Wyatt, *The Disruptive Impact of Lethal Autonomous Weapons Systems Diffusion: Modern Melians and the Dawn of Robotic Warriors* (New York, NY: Routledge, 2021); and Andrew Futter, "Disruptive Technologies and Nuclear Risks: What's New and What Matters," *Survival* Vol. 64, No. 1 (2022), pp. 99-120; James Johnson, "Artificial Intelligence & Future Warfare: Implications for International Security," *Journal Defense & Security Analysis* Vol. 35, No. 2 (2019); Todd S. Sechser, Neil Narang, and Caitlin Talmadge, "Emerging Technologies and Strategic Stability in peacetime, crisis, and war," *Journal of strategic studies* Vol. 42, No. 6 (2019), pp. 727-735; Michael C. Horwitz, "When speed kills: Lethal autonomous weapon systems, deterrence and stability," *Journal of Strategic Studies* 42 (2019), pp. 764-788, https://doi.org/10.1080/01402390.2019.1621174; Jacquelyn Schneider, "The Capability/Vulnerability Paradox and Military Revolutions: Implications for Computing, Cyber, and the Onset of War," *Journal of Strategic Studies* Vol. 42, No. 6 (2019): 841-863; Michael C. Horowitz, "Do Emerging Military Technologies Matter For International Politics?," *Annual Review of Political Science* Vol. 23 (2020), pp. 385-400; Rupal N. Mehta, "Extended Deterrence and Assurance in an Emerging Technology Environment," *Journal of Strategic Studies* Vol. 44, No. 7 (2021), pp. 958-982, https://doi.org/10.1080/01402390.2019.1621173.

Footnote 4: See also Rebecca Slayton, "What Is the Cyber Offense-Defense Balance? Conceptions, Causes, and Assessment," *International Security*, Vol. 41, No. 3 (Winter 2016/17), pp. 72–109; and Lennart Maschmeyer, ""The Subversive Trilemma: Why Cyber Operations Fall Short of Expectations," *International Security* Vol. 46 No. 2 (2021), pp. 51–90.

Footnote 8: See also James Fearon, "The Offense-Defense Balance and War Since 1648," Paper presented at the Annual Meetings of the International Studies Association, Chicago, Illinois, 21-25 February 1995, pp. 6-7.

Footnote 9: Klaus Schwab, *The Fourth Industrial Revolution* (New York, NY: Crown Business, 2016); Ajay Agrawal, Joshua Gans, and Avi Goldfarb, *Prediction Machines: The Simple Economics of Artificial Intelligence* (Boston: Harvard Business Review Press, 2018).

Footnote 10: Paul Ingram, "Will Trident Still Work in the Future?" Short policy brief (BASIC, 22 January 2016), pp. 8-17; James Holmes, "Sea Changes: The Future of Nuclear Deterrence," *Bulletin of the Atomic Scientists*, Vol. 72, No. 4 (July 2016), pp. 228–233; Elizabeth Mendenhall, "Fluid Foundations: Ocean Transparency, Submarine Opacity, and Strategic Nuclear Stability," *Journal of Military and Strategic Studies* Vol. 19, No. 1 (October 2018), pp. 119-158; Zachary Kallenborn, "If the Oceans Become Transparent," *Proceedings* Vol. 145, No. 10 (October 2019); Roger Bradbury *et al.*, *Transparent Oceans? The Coming SSBN Counter-Detection Task May Be Insuperable* (Acton, Australia: National Security College, The Australian National University, 2020); Roger Bradbury, "The Sub Story No One Wants to Hear," *Defense Connect* (September 22, 2021), https://www.defenceconnect.com.au/blog/8792-the-sub-story-no-one-wants-to-hear; and Tory Shepherd, "Will All Submarines, Even Nuclear Ones, Be Obsolete and 'Visible' by 2040?," *The Guardian* (October 4, 2021), https://www.theguardian.com/australia-news/2021/oct/05/will-all-submarines-even-nuclear-ones-be-obsolete-and-visible-by-2040.

Footnote 12: For a sober assessment, see Adrian Cho, "The Short, Strange Life of Quantum Radar," *Science* Vol. 369, No. 6511 (Sep 2020), pp. 1556-1557.

Footnote 14: See also Mike (Mihajlo) Mihajlovic and Djordjie S. Anicic, *Missileers Against Stealt: The First Downing of the Stealth Fighter in History* (Toronto, Canada: MSM Publishing, 2019), p. ii.

Footnote 15: While this specific claim has been contested, the importance of radar is unquestioned. See Tony Devereux, *Messenger Gods of Battle: History of Electronic Warfare* (London, UK: Brassey's, 1991), p. xvi.

Footnote 17: See also and Jon R. Lindsay, *Information Technology and Military Power* (Ithaca, NY: Cornell University Press, 2020), chapter 3. The search for the word "radar" in *American Political Science Review* yields 119 entries. Of these, the great majority employs the term metaphorically (e.g., "beneath the political radar screen"). The remaining articles employs the word casually, mentioning the technology together with others (e.g., "radar, jet aircraft, missiles."). We could find no article that explores specifically the implication of radar for world politics. Things are only slightly better with *International Organization*. Of the 47 entries for the word "radar", only four articles mention (briefly) the application, employment or implications of radar. See Robert H. Cory, "International Inspection: From Proposals to Realization," *International Organization* Vol. 13, no. 4 (Autumn 1959), pp. 495–504; Phillip Taylor, "Weapons Standardization in NATO: Collaborative Security or Economic Competition?" *International Organization* Vol. 36, no. 1 (Winter 1982), 95–112; Marvin S. Soroos, "The Commons in the Sky: The Radio Spectrum and Geosynchronous Orbit as Issues in Global Policy," *International Organization* Vol. 36, no. 3 (Summer 1982): 665–77; and Stephanie G. Neuman, "International Stratification and Third World Military Industries," *International Organization* Vol. 38, no. 1 (Winter 1984), pp. 167–97. The majority of the other entries are summaries of meetings of international organizations such as the General Assembly of the United Nations, the International Bank for Reconstruction and Development, the International Civil Aviation Organization, the, Intergovernmental Maritime Consultative Organization, or the World Meteorological Organization.

Footnote 19: See also George N. Lewis, Steve Fetter, and Lisbeth Gronlund, "Casualties and Damage from Scud Attacks in the 1991 Gulf War," *DACS Working Paper*, MIT Defense and Arms Control Studies Program (March1993); Jeremiah D. Sullivan, Dan Fenstermacher, Daniel Fisher, Ruth Howes, O'Dean Judd and Roger Speed, "Technical Debate over Patriot Performance in the Gulf War," *Science & Global Security*, Volume 8 (1999), pp. 41-98.

Footnote 27: See also D.B. Des Roches, "The Siren Song of the Drone: Understanding the Factors Driving GCC Drone Acquisition," *Al Jaazera Centre for Studies* (May 1, 2021).

Footnote 28: In the article, H.I. Sutton reports the words of "Defense analyst Tayfun Ozberk, a retired naval officer". Sutton writes that "Although not fully stealthy, the Bayraktar [TB2] features a low radar cross-section (RCS). Together with its relatively low altitude and slow speed, this makes it difficult for classical radars to track." Sutton then quotes Zoberk as saying that the TB2 "It is a low-slow-flyer (LSF), and you know it is a challenge for classical radars to detect LSFs already. And its RCS makes it even harder." Along the same lines, Bishara A. Bahbah writes that because "of their generally small size and ability to fly at low altitudes, drones can fly under most countries' radar systems, even when their targets possess highly advanced anti-aircraft and anti-missile defense." See also James Rogers and Dominika Kunertova, *The Vulnerabilities of the Drone Age Established Threats and Emerging Issues out to 2035* (Zurich, Switzerland: Center for Security Studies of ETH-Zurich, 2022), pp. 2 and 4.

Footnote 30: See also Zachary Kallenborn, "Swarms of Mass Destruction: The Case for Declaring Armed and Fully Autonomous Drone Swarm as WMD", *Modern War Institute*, May 28, 2020. https://mwi.usma.edu/swarms-mass-destruction-case-declaring-armed-fully-autonomous-drone-swarms-wmd/ Amy McCullough, "The Looming Swarm", *Air Force Magazine*, March 22, 2019. https://www.airforcemag.com/article/the-looming-swarm/ ; and Paul Iddon, "Can Iranian Drone Tech Shift Middle East's Strategic Balance Of Power?"*Arab News* (may 24, 2021), https://www.arabnews.com/node/1864131/middle-east.

Footnote 39: For a more specific discussion, see Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability: Analysis and Design, 2nd Edition* (Reston, VA: American Institute of Aeronautics and Astronautics, 2003).

Footnote 40: See also Jonathan Shimshoni, "Technology, Military Advantage, and World War I: A Case for Military Entrepreneurship," *International Security* Vol. 15, No. 3 (Winter 1990/91), pp. 190–191.

Footnote 42: Some works, not explicitly focused on the ODB, have studied stealth. See for example Jasper Welch, "Assessing the Value of Stealthy Aircraft and Cruise Missiles," *International Security* Vol. 14, no. 2 (1989), pp. 47–63, https://doi.org/10.2307/2538854; and John W. R. Lepingwell. "Soviet Strategic Air Defense and the Stealth Challenge." *International Security* Vol 14, no. 2 (1989), pp. 64–100, https://doi.org/10.2307/2538855.

Footnote 43: As Martin Van Creveld has written, in the aerial domain "technology is required not merely in order to fight but for sheer survival. If only for this reason, and everything else being equal, the simpler the environment the greater the military benefits technological superiority can confer. By contrast, the terrestrial environment is much more complex... a complex environment, more than a simple one, tends to give the advantage to the superior tactician. That side wins that is best able to comprehend the totality of factors involved, and then uses them to advantage." Martin van Creveld, *Technology and War: From 2000 B.C. to the Present* (New York: Touchstone, 1989), p. 229.

Footnote 49. This assumption is consistent with some of the writings in the ODB literature. For example, Glaser and Kaufmann, write that "a change that shifts the balance in a given direction at one level will usually also shift it in the same direction at all higher levels. Since any strategic offensive necessarily requires offensive operations, and offensive operations require offensive tactical battles, a change that makes tactical offense harder will usually also make operational offense harder, which in turn makes strategic offense more difficult." Charles L. Glaser and Chaim Kaufmann, "What Is the Offense-Defense Balance and Can We Measure It?" *International Security* 22, no. 4 (Spring 1998):

Footnote 50: As Biddle writes, "For offense-defense theory's purposes, the crucial military outcome is thus whether the invader can win a given operation decisively enough to end a war quickly." Biddle, "Rebuilding the Foundations of Offense-Defense Theory," p. 748.

Footnote 51: Over the years, the literature on ODB has come to focus more and more on an economic definition of the ODB, which looks at the relative cost of defense vis-à-vis the offense – i.e., for every dollar spent by the offense, how much the defense should spend. See for example Stephen Van Evera, "The Cult of the Offensive and the Origins of the First World War," *International Security*, Vol. 9, No. 1 (Summer 1984), p. 5, fn.1; and Glaser and Kaufmann, "What Is the Offense-Defense Balance," pp. 73-74. As Adams, Biddle and Lieber have pointed out, however, this approach suffers of several problems. Most prominently, an ex-ante and objective operationalization of the relative cost of defense vis-à-vis the offense is close to impossible. Adams, "Attack and Conquer?," p. 51; Biddle, "Rebuilding the Foundations of Offense-Defense Theory," p. 749, fn. 12; Lieber, *War and the Engineers*, p. 28. Biddle, for instance, explains that "Orthodox offense-defense theory uses a variety of dependent variable operationalizations, but the most prominent of these is the dollars an attacker must invest in offensive capability to offset one dollar of opposing investment in defensive capability […] This definition, however, makes the balance unobservable even in principle. The historical record can show what combatants actually spent, but not what they needed to spend in order to offset their opponents' investments. The investment ratio definition requires one to estimate how much more a war's loser would have had to have spent in order barely to prevail or how much less the winner could have spent and still barely have won. Either calculation is necessarily a counterfactual, not an observable quantity." Biddle, "Rebuilding the Foundations of Offense-Defense Theory," p. 749, fn. 12. Moreover, a proper economic assessment of the ODB would have to include also relative benefit of conquest. See Robert Gilpin, *War and Change in World Politics* (Cambridge: Cambridge University Press, 1981), p. 63; and Fearon, "The Offense-Defense Balance and War Since 1648," pp. 4-6. However, including such a consideration creates more problems than it addresses. See Levy, "The Offensive/Defensive Balance of Military Technology," p. 227. Additionally, the benefit of conquest is inherently subjective, and calculating it at the systemic level is impossible given that the value of a given territory is highly contextual. Along the same lines, we add, the cost of defense vs offense should also include economic sanctions on the attacking country, if they are imposed, which would deprive the whole discussion on the ODB of its real purposes. There is more, with the exception of extreme cases, the relative cost of defense vs offense tells us more about the balance of power than about the ODB – this problem violates the very approach of the ODB literature that has tried to identify a variable that is different from the balance of power. For these reasons, some scholars have used the relative casualties to define the ODB. See Quester, *Offense and Defense in the International System*, p. 2; and Biddle, "Rebuilding the Foundations of Offense-Defense Balance," p. 749. Finally, for air warfare, an economic operationalization of the ODB would fail to capture a major change in the ODB, such as the coming age of defense-dominance brought about by radar and surface-to-air missiles, in light of the extraordinary cost of these technologies. As mentioned above, the Soviet deployment of surface-to-air missile batteries along its territory cost about $30 billion, in comparison to the $25 billion that the Apollo program cost at that time. This would mean that surface-to-air missiles, the one that shot down state-of-the-art aircraft like the B-52, C-130, F-4, F-105, F-111 and the U2 making penetrating enemy's air defense impossible, would not qualify as a defense-enhancing technology. This would also mean that if the United States had turned to WWII-era aircraft like the B-17 *Fortress* or the B-24 *Liberator*, it would have shifted the ODB towards the offense because of their much lower cost.

Footnote 53: See also Justin Bronk, "Modern Russian and Chinese Integrated Air Defence Systems: The Nature of the Threat, Growth Trajectory and Western Options," *RUSI Occasional Paper* (January 2020).

Footnote 54: See also Carlo Kopp, "Evolving Technological Strategy in Advanced Air Defense Systems," *Joint Force Quarterly* No. 57 (Spring 2010), pp. 86-93.

Footnote 59: Prominent air power theorists, such as Giulio Douhet, Billy Mitchell, and John Warden have provided the basis for what constitute the offensive advantage in air operations. Other scholars, primarily associated with the Air University at the Maxwell Air Force Base, have further elaborated on these writings. They have focused on the speed, range, maneuverability and the capacity to concentrate (mass). These parameters, however, are historically contingent. While speed and range (and altitude) did make bombers invulnerable to air defenses in the 1930s, as Douhet predicted, from the 1960s this was no longer the case. Accordingly, we abstract away to two key principles: avoidance and saturation.

Footnote 60: Early warning radars (which have long range but low resolution) scan the horizon for possible threats and inform the rest of the IADS of an incoming intruder, and then command and control centers pass the potential target to acquisition radars (which have higher resolution but shorter range) that identify the intruder as either friend or foe and, if needed, track it and then proceed to terminal engagement.

Footnote 62: Dennis M. Gormley, "Missile Defense Myopia: Lessons from the Iraq War," *Survival* 45, No. 4 (Winter 2003-04), p. 62. Dennis M. Gormley, *Dealing with the Threat of Cruise Missiles*, Adelphi Paper 339 (London: International Institute for Strategic Studies, 2001), pp. 11, 62; Thomas G. Mahnken, *The Cruise Missile Challenge* (Washington, DC: Center for Budgetary and Strategic Assessment, 2005), pp. 11, 21 and 43.

Footnote 63: For a more technical discussion see Daniel P. Meyers and Herbert A. Mayer, *Radar Target Detection: Handbook of Theory and Practice* (New York, NY: Academic Press, 1970), pp. 36-82.

Footnote 64: Precisely, the RCS of an object is a function of the target size, shape and material, of the angle and azimuth of incidence, of the radar frequency, as well as of the polarizations of the transmitting and receiving antennae. The wavelength of a radar pulse measures the distance between two peaks – i.e., the distance over which the wave's shape repeats.

Footnote 66: This is why air-control radar operate a number of different frequencies. See Merrill Skolnik, "An Introduction and Overview of Radar," in Merrill Skolnik (ed.), *Radar Handbook – 3rd Edition* (New York, NY: McGrawHill, 2008), p. 1.9.

Footnote 67: Wavelength and frequency are inversely related. Most radars operate between 0.67m and 3.16m (200mMHz and 95GHz). Over-the-horizon radars operate at 14-150m wavelength (2-20MHz), early warning radars operate at, surveillance radars operate at 15cm-10m wavelength (1GHz-30MHz), target acquisition radars operate at 3.75-2.5 cm wavelength (8-12GHz).

Footnote 69: This is the "Rayleigh region" of radar scattering, and the RCS will be proportional to the inverse fourth power of the wavelength. But the Rayleigh region of radar scattering is extremely unlikely for aerial vehicles. Consider the problem faced in the 1950s by the U.S. and Canada. The continuous wave radars of the Distant Early Warning (DEW) line detected large birds, thus leading to many false alarms. Radar engineers working on this problem thought about increasing the wavelength of operation so as to bring the interaction between these birds and the radar waves in the "Rayleigh region" – i.e., make sure that radars would miss these birds. Yet, even at longer wavelength, birds would still appear on radar screens. See Merrill I. Skolnik, "Fluttar DEW-Line Gap-Filler," in Nicholas J. Willis and Hugh D. Griffith, (eds.) *Advances in Bistatic Radar* (Raleigh, NC: SciTech Publishing, 2007), 37-38.

Footnote 70: The type of backscattering described in the text is called the "resonance region." In the words of a Lockheed Martin engineer with experience in the field, the four most important aspects for reducing the radar cross section of an object are "shape, shape, shape and materials." Denys Overhol quoted in David Axe, "Seven Secret Ways America's Stealth Armada Stays Off the Radar," *Wired*, December 13, 2012, https://www.wired.com/2012/12/steath-secrets/. See also Alfred Price, *The History of Electronic Warfare, Volume III: Rolling Thunder Through Allied Force, 1964 to 2000* (Alexandria, VA: Association of Old Crows, 2000), p. 98. For a technical but accessible explanation, see for example Dan Katz, "Physics and Progress of Low-Frequency Counterstealth Technology," *Aviation Week & Space Technology* (August 25, 2016). To fully appreciate how the relationship between size and RCS is non-linear, consider that while an F-16 *Falcon*, whose wingspan is 10m, has a RCS of 4sqmt, the B-1 *Lancer*, with 42m wingspan, has a RCS of 2sqmt. On the F-16, see Tobias Naegele, Dashton Parham and Mike Tsukamoto, "The B-2 at 30: Improving with Age," *Air Force Magazine* (July 1, 2019). On the B-1, see Thomas Withington and Mark Styling, *B-1B Lancer Units in Combat* (London, UK: Osprey Publishing, 2006), p. 13. This weak relationship appears even more evident when we consider MALE drones: the *Anka* produced by Turkish Aerospace Industry has a wingspan of 17.5m and a RCS of 1sqmt, which means that, its wingspan and RCS are respectively, twice and one-fourth those of the F-16, and less than half and half those of the B-1. The same logic is true for the MALE drone *TB2* (12m) produced by the Turkish company Bayraktar, whose RCS is 0.5sqmt. On the *Anka* and the *TB2*, the technical data comes from an aerospace manager who asked not to be named.

Footnote 71: In principle, the size of an object would be relevant when the wavelength of the incoming radar pulse is smaller than the target size. But this is true only for an object with a perfectly spherical shape. In this case, the RCS will be about the same as the real area of the target, and hence size will have a direct effect on detection. Because the RCS approaches the optical value, this condition is called the "optical region."

Footnote 73: As recalled by the lead designer of the first stealth aircraft, the F-117 *Nighthawk* stealth technology requires "absolutely smooth surfaces…" One morning, the prototype of the stealth fighter flew "against the radar range and was lit like a goddam Christmas tree…" The problem stemmed from the fact that the heads of three screws were not quite tight and extended above the surface by less than an eighth of an inch. On radar they appeared as big as a barn door!"

Footnote 75: Su Haoqin, Bao Xiaoxiang, Li Jianhua, Liu Kai, Cen Mengxi, Song Jing, "Calculation and Analysis on Stealth and Aerodynamics Characteristics of a Medium Altitude Long Endurance UAV," *2014 Asia-Pacific International Symposium on Aerospace Technology, APISAT2014*; C. Zhang, Q. M. Cai, X. Cao, M. Zhu, Y. Zhu and Y. -W. Zhao, "Research on Radar Scattering Modeling and Characteristics of Moving Unmanned Air Vehicle Above a Randomly Rough Surface," *2020 9th Asia-Pacific Conference on Antennas and Propagation (APCAP)*, Xiamen, China, 2020, pp. 1-2, doi: 10.1109/APCAP50217.2020.9245977; and Oleg Sukharevsky, Vitaly Vasylets, Ivan Kozhedub, Valery Orlenko and Ivan Ryapolov, "Radar scattering characteristics of a UAV model in X-band," in *IET Radar, Sonar & Navigation*, vol. 14, no. 4 (April 2020), pp. 532-537, doi: 10.1049/iet-rsn.2019.0243.

Footnote 76: This is also why the first stealth aircraft, the F-117 *Nighthawk*, did not carry any radar. See Stimson, *Introduction to Airborne Radar*, p. 31.

Footnote 78: This is captured by the inverse fourth power law of the radar range equation: $S_e = \frac{P_r}{4\pi R^4}$, where S_e is the power density at the receiving place, the radar; P_r is the power reflected by the target; R is the range between the target and the radar. As the range between target and radar increases, the electro-magnetic energy received by the radar diminishes at an accelerating rate – the fourth power of the range (in km) multiplied by 4π. For a more technical overview, see Daniel P. Meyers and Herbert A. Mayer, *Radar Target Detection*, pp. 1-18.

Footnote 80: This is consistent with other calculations using publicly available data. Consider table A1, reported below.

Table A1 – RCS and Range of Detection

RCS (m^2)	RCS (dB)	Fighter AESA Radar Range (mi)	Early Warning Radar Range (mi)
1	0	100	300
.1	-10	56	168
.01	-20	32	95
.001	-30	18	53
.0001	-40	10	30
.00001	-50	6	17
.000001	-60	3	9

Source: Barrett with Mace Carpenter, *Survivability in the Digital Age*, p. 3

Along the same lines, consider the estimated range of detection of the radar mounted on the Russian Sukhoi Su-35 and on the Russian ground air-defense system S-400's 92N6E. While the Su-35 could detect conventional jet fighter such as the F-15 *Eagle* at 335-370 miles distance; it would be able to detect a stealth fighter like the F-22 at only 22 miles distance. Similarly, while the S-400 could detect an F-15 at 195-215 miles; it could detect an F-22 at only 13 miles distance. See Dan Katz, "Measuring Stealth Technology's Performance," *Aviation Week & Space Technology* (June 28, 2016). For a technical discussion, see Fred E. Nathanson with J. Patrick Reilly and Marvin N. Cohen *Radar Design Principles: Signal Processing and the Environment – Second Edition* (Mendham, NJ: SciTech Publishing, 1999), p. 184.

Footnote 83: More advanced sensors rely on semiconductors such as gallium nitride (employed, for example, in the U.S. Patriot) that allow for much more power, and hence for longer range as well as for superior acuity. Moreover, the exploitation of the shift in frequency resulting from the moving of an object (Doppler effect, discussed later) permits to more accurately distinguish incoming threats from aerial clutter. Finally, the application of machine learning to signal processing allows for much lower detection thresholds, and hence to distinguish a target from the background with much lower signal-to-noise (clutter) ratio.

Footnote 84: Already in the 1980s, the Soviet short-range air defense system ZSU-23-4 was thought of being capable of "tracking targets with a radar cross section of 0.1 squared meters or larger." Director of Central Intelligence, *Special National Intelligence Estimate*: *Soviet Reactions to Stealth SNIE 11-7/9-85/L* (Langley, VA: Central Intelligence Agency, 1985), (August 1985), p. 15, https://www.cia.gov/readingroom/docs/DOC_0000261288.pdf.

Footnote 85: With regard to the jamming capabilities of the F-35, we learned about this through a conversation with a technical expert with close experience with the F-35 program.

Footnote 88: For instance, when illuminated from the sides or from the rear, small vehicles such as cruise missiles and drones might have a RCS that is similar to that of much larger vehicles, such as that of the Russian Tu-22M3 variable-wing bomber This point refers specifically to the RCS of a standard cruise missile and of the Tu-22M3 from the side (90° azimuth) in the computer simulation. See Sukharevsky, ed., *Electromagnetic Wave Scattering by Aerial and Ground Radar Objects*, pp. 75-83 and 151-160. This is why the first stealth aircraft, F-117 *Nighthawk*, could be shot down in the former Yugoslavia in 1999. Namely, its "radar signature was much greater from its side aspect and in other frequency ranges, including frequencies used by long-rage early warning systems… These characteristics made it possible for the F-117 to be tracked from the side or with early warning radars." See Clark and Gunzinger, *Winning the Airwaves*, p. 12 and p. 12 fn. 18.

Footnote 91: See also Grave V. Jean, "Remotely Piloted Aircraft Fuel Demand for Satellite Bandwidth," *National Defense Magazine*, July 2011; *RPA Vector: Vision and Enabling Concepts, 2013–2038, United States Air Force* (Department of Defense Washington, DC, 17 February 2014), pp. 18–24; Defense Science Board, *Study on Unmanned Aerial and Uninhabited Combat Aerial Vehicles* (Washington, DC, 2004), p. 24; Congressional Budget Office, *Policy Options for Unmanned Aircraft Systems* (Washington, DC, 2011); Stew Magnuson, "Military Wrestles With the High Cost of Satellite Terminals," *National Defense Magazine*, February 2014.

Footnote 93: This is what the U.S. did in the late 1960s, with the QRC-248 enemy IFF transponder interrogator. The U.S. figured out how to use the Soviet airborne identification system, and used the QRC-248 to identify Soviet MiGs among countless radar returns.

Footnote 94: See also Bronk, *Modern Russian and Chinese Integrated Air Defence Systems*, p. 12.

Footnote 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 will shrink. Similarly, by elevating a radar by 20 or 30 meters from the ground, radars operators can reduce the radar shadow – i.e., both the altitude at which aircraft can fly without being illuminated, and the range at which they are immune of detection, for every altitude profile.

Footnote 96: See also James Holland, *Dam Busters: The True Story of the Inventors and Airmen Who Led the Devastating Raid to Smash the Germans Dams* (New York, NY: Atlantic Monthly Press, 2012).

Footnote 97: Low-altitude flight entails the risk of collision with unexpected objects, whether natural (e.g., hills and trees) or artificial (buildings and bridges). This problem was solved in the 1970s with Terrain Contour Matching (TERCOM), a navigation system that uses a pre-recorded contour map of the terrain that is matched in real time with measurements made during flight by an on-board radar altimeter. Stimson, *Introduction to Airborne Radar*, pp. 38-40. See also Geoffrey B. Irani and James P. Christ, "Image Processing for Tomahawk Scene Matching," *Johns Hopkins APL Technical Digest*, Volume 15, Number 3 (1994), pp. 250-264.

Footnote 99: See also Stimson, *Introduction to Airborne Radar*, pp. 24-25. Guglielmo Marconi had understood early on that by increasing the elevation of transmitters, he could extend the range of radio transmission. See Marc Raboy, *Marconi: The Man Who Networked the World* (Oxford, UK: Oxford University Press, 2016), pp. 96-97.

Footnote 101: These systems are, for example, the US-made E-3 Sentry (AWACS) and the E-2 Hawkeye (AEW), and the current generation of HALE UAVs such as the RQ-4B Global Hawk drones that can be equipped with the state-of-the-art multi-platform radar technology (MP-RTIP). In addition, several defense firms, like Airbus, Boeing, Thales and others, are developing solar-powered High-Altitude Platform-Systems (HAPS) that will have the capability to operate constantly in the stratosphere. See "E-2D specifications", NAVAIR, https://www.navair.navy.mil/product/E-2D; "E-3 Sentry AWACS specifications", https://www.airforce-technology.com/projects/e3awacs/; Congressional Budget Office, *National Cruise Missile Defense: Issues and Alternatives* (Washington, DC: Press of the United States of America, 2021); Colonel Michael S. Maloney, "Cruise Missile Attack: Are We Prepared?", *US Army War College*, March 2007. For the HAPS see Nate Miller, Cameron Scott and Troy Thomas, "How ISR

Tech Will Disrupt the Market for Defense Drones", *Boston Consulting Group (BCG)*, February 2020, https://www.bcg.com/it-it/publications/2020/isr-tech-disrupt-market-defense-drones and Airbus, "The Airbus Zephyr, Solar High Altitude Platform Station (HAPS) concludes a successful new test flight campaign in Arizona, USA", December 2020, https://www.airbus.com/en/newsroom/press-releases/2020-12-the-airbus-zephyr-solar-high-altitude-platform-station-haps.

Footnote 103: In the specific case of the United States, the deployment of 92 drones (MQ-9, MQ-4C, RQ-4 and MQ-1C) could be sufficient to monitor constantly both the Western Pacific and Eastern Europe areas, with an estimated operating cost of approximately $1.4 billion per year.

Footnote 107: Of course, ground-based air defense systems will have a relatively limited time-window to detect, identify, locate and engage an incoming MALE UAV, but while tight, such time-window will still be sufficient for proficient operators – and provides an additional opportunity in addition to that offered by airborne platform.

By considering a cruise missile flying at 500 miles per hour at 300 feet of altitude, we can list the response time needed to identify, locate, and engage it with different radar sensors. Employing a ground-based radar with a detection range of about 25 miles (given by the horizon-limit), the response time would be 3 minutes. Elevating the radar to 700 feet (for example, placing it onto a tower) could increase its detection range to 60 miles and the available response time to 7 minutes. For airborne radar systems like Aerostats and Surveillance Aircrafts, detection range and response time would increase significantly. For example, a radar on aerostat would have a detection range of 165 miles at 10,000 feet, with a response time of 18 minutes to identify, locate and engage a generic subsonic cruise missile. The US-made E-3 Sentry (AWACS) flying at 30,000 feet of altitude would have a detection range of its radar of about 270 miles covering about 230,000 square miles and ensuring 32 minutes of warning time to react and defend against an incoming cruise missile. A High-Altitude Unmanned Aircraft (HALE UAV) such as the RQ-4B Global Hawk can be equipped with radar sensors able to detect incoming target at 370 miles at 60,000 feet. In this case the response time would be increased to 44 and 88 respectively for a cruise missile and a MALE drone. Given that the maximum speed of a MALE UAV is about half that of a cruise missile (between 100 and 250 miles per hour), the available response for air defense would be at least twice as long as that for a cruise missile. Once the target is identified and localized, there are many options to engage and destroy it. Two main options are airborne interceptors (a jet-fighter) and surface to air missiles (SAMs). The former needs between 5 and 10 minutes to receive the orders and to take off (assuming no patrolling aircraft is available). The latter needs at least 5 minutes to identify and localize the target and engage it. Between these two options, SAM have two advantages: they are faster to launch and they fly at a much higher speed than a jet fighter. Aircraft interceptors, however, have longer range. Both have the capabilities to take down the target within the time limit. See Congressional Budget Office, *National Cruise Missile Defense*, pp. 21-31.

Available information from the War in Ukraine suggests that radar masts might have a significant range of detection. According to Justin Bronk and co-authors, who carried out interviews with Ukrainian Air Force personnel, the "Russian S-band 48Ya6 'Podlet-K1' all-altitude radar", which relies on a mast to enhance its elevation from the ground, and hence increase its range of detection, " have allowed Russian forces to track Ukrainian fixed-wing and rotary sorties at altitudes as low as 15 ft at well over 150 km." Justin Bronk with Nick Reynolds and Jack Watling, *The Russian Air War and Ukrainian Requirements for Air Defence* (London, UK: Royal United Services Institute for Defence and Security Studies, 2022), p. 12.

Footnote 108: Stillion and Orletsky's discussion about slow-flying cruise missiles applies also in the case of MALE UAVs, since their slow speed is "potentially both their biggest advantage and their biggest disadvantage.” In fact, “when combined with predictable, computer-controlled flight paths, their slow speed and small size make them near-ideal targets for optically aimed medium and heavy machine guns.” 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 Corporation, 1999), p. 45. On layered defense, see for example Steven P. Bucci, “Diverse, Layered Missile Defense Is Key to Killing Drone Swarms,” *Defense News* (October 2, 2019). On the integration of MANPADS, SHORAD, MEADS and LORAD, see for example the summary in Bronk, *Modern Russian and Chinese Integrated Air Defence Systems*; pp. 17-18.

Footnote 111: Flying at 200m altitude, the *Lancer* could remain in the “radar shadow” until it was about 80km from an enemy’s radar outpost. Since the *Lancer* carried missiles with a range much longer than 80km, it could then safely launch them against its designated target. The AGM-69 Short-Range Attack Missile (SRAM) produced by Boeing is a supersonic missile with a range of about 160km. The AGM-86 Air-Launched Cruise Missile (ALCM) is a subsonic missile with range up well above 1,000km (1,111km for the AGM-86C, and 2,414Km for the AGM-86B). See Congressional Budget Office, *B-1B Bomber and Options for Enhancements*, pp. 89-90; “AGM-86B/C/D Missiles,” *US Air Force* (May 24, 2010), https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104612/agm-86bcd-missiles/.

Footnote 115: Filippo Neri, *Introduction to Electronic Defense Systems* (London, UK: Artech House, 2018), pp. 82-88.

Footnote 119: See also Philip E. Pace, *Detecting and Classifying Low Probability of Intercept Radar* (Norwood, MA: Artech House, 2009), p. 246; and Hai Deng and Zhe Geng, *Radar Networks* (Boca Raton, FL: CRC Press, 2020), p. 124.

Footnote 122: The same phenomenon explains the change in sound frequency of an approaching and a departing ambulance. Stimson, *Introduction to Airborne Radar*, pp. 10-11. Early moving target indicator (MTI) radars took advantage of other changes, such as in phase, resulting from a moving target. See for example Greenspan, “The Evolutionary Development of Airborne Surface Moving Target Detection.”

Footnote 124: As Valkenburg notes, “Digital processing makes it possible to automatically detect and accurately track many hundreds or thousands of targets so as to present fully processed tracks rather than individual detections or “raw” (unprocessed) radar data.” Mac E. Van Valkenburg, *Reference Data for Engineers Radio, Electronics, Computer & Communications* (Hoboken, N.J.: Elserver, 2001). p. 36.4.

Footnote 128: For long-dated capabilities, see for example Skolnik, “Fluttar DEW-Line Gap-Filler,” p. 39. Since the 1980s, advances in signal processing have permitted to enhance the received signal of slow-moving (and low-flying) objects that can be masked by surface clutter. See Robert E. Thurber, “Advanced Signal Processing Techniques for The Detection of Surface Targets,” *Johns Hopkins APL Technology Digest* Vol. 4, No. 4 (1983): 285-295, https://www.jhuapl.edu/Content/techdigest/pdf/V04-N04/04-04-Thurber.pdf. For recent advances, see François Le Chevalier, “Space-Time Coding for Active Antenna Systems,” in Melvin and Scheer, *Principles of Modern Radar Vol. II*, pp. 501 and 525; Ballard and Kemkemian, “Fire-Control Radar,” pp. 134-137; and Richards, *Fundamentals of Radar Signal Processing*, pp. 501, 524, and 529-530.

Footnote 130: See also Bahret, “The Beginnings of Stealth Technology.”

Footnote 131: See also John Paterson, "Technology's Effects on Combat Aircraft Survivability," *Journal of Aerospace* Vol. 106, No 1 (1997), pp. 1515-1530; and Grant, *The Radar Game*, pp. 29-46. Lynch, *RF Stealth*, p. 1.

Footnote 132: Tracking radars (or target acquisition radars) operate in the X-band frequency (8-12GHz). Because of their short wavelength (3.75-2.5 cm), tracking radar allow for higher resolution, which in turn permit target identification, tracking and discrimination. In turn, the short wavelength of tracking radar suffers of significant attenuation (radar power being absorbed by water vapor and oxygen). This means that radars operating in the X-band frequency have a more limited range in comparison to lower, but less precise, frequencies (i.e., L-band or S-band). For a graph, see slides 8 and 9 in "Introduction to Radar Systems Propagation Effects Propagation-1 RJG 7/31/2008," *MIT Lincoln Laboratory*, https://www.ll.mit.edu/sites/default/files/outreach/doc/2018-07/lecture%203.pdf.

Footnote 133: For a general discussion about advances in air defense and the threat of drones, see for example Robbin Laird, "Dealing with the Drone Threat to the Ground Maneuver Force: The Weibel Solution Set," *Defense.Info,* July 22, 2022 (https://defense.info/multi-domain-dynamics/2022/07/dealing-with-the-drone-threat-to-the-ground-maneuver-force-the-weibel-solution-set/)

Footnote 134: See also Stimson et al., *STIMSON's Introduction to Airborne Radar*, pp. 30-31; and Jack Brown, "GaN Extends Range of Army's Q-53 Radar System," *Microwaves&RF* (16 October 2018), https://www.mwrf.com/markets/defense/article/21849404/gan-extends-range-of-armys-q53-radar-system. For appreciating the importance of these new semiconductors, see for example Raymond Bonner and Christine Spolar, "Death in Singapore," *Financial Times* (February 15, 2013), http://ig-legacy.ft.com/content/afbddb44-7640-11e2-8eb6-00144feabdc0; and Stephen Bryen, "The Stealthy Gallium War," *Bryen's Blog* (undated), http://www.bryensblog.com/stealthy-gallium-war/.

Footnote 135: In this regard, Russia has also brought back radars operating in the VHF band frequency. Despite the name of the band (very high frequency), these radars operate at very low frequency, which in turn permit them to detect at long range fight-sized stealth aircraft. For a discussion, see Carlo Kopp, "Russian VHF Counter Stealth Radars Proliferate," *Defence Today* Vol.7. No.3 (2008); and Guy Plopsky and Fabrizio Bozzato, "The F-35 vs. The VHF Threat," *The Diplomat* (August 21, 2014), https://thediplomat.com/2014/08/the-f-35-vs-the-vhf-threat/.

Footnote 136: Bing, Ehrman and Selee, "Automatic Target Recognition," pp. 631-668; Stephen L. Pendergast, "Recent Advances in Radar Technology," *Microwave Journal* (September 2015), pp. 6-28; and Ping Lang, Xiongjun Fu, Marco Martorella, Jian Dong, Rui Qin, Xianpeng Meng, and Min Xie, "A Comprehensive Survey of Machine Learning Applied to Radar Signal Processing," Working Paper (September 2020), https://arxiv.org/pdf/2009.13702.pdf.

Footnote 137: See also Willis and Griffiths (eds.), *Advances in Bistatic Radar*; Victor Chernyak, "Multisite Radar Systems Composed of MIMO Radars," *IEEE Aerospace and Electronic Systems Magazine* Vol. 29, no. 12 (December 2014), pp. 28–37; Neri, *Introduction to Electronic Defense Systems*, pp. 536-538; Deng and Geng, *Radar Networks*. For a less technical discussion, see for example Bill Sweetman, *Stealth Aircraft* (Osceola, WI: Motorbooks International, 1986), pp. 35-39; Stimson, *STIMSON's Introduction to Airborne Radar*, p. 597-696; and Arend G. Westra, "Radar versus Stealth Passive Radar and the Future of U.S. Military Power," *Joint Force Quarterly* No 55 (4th Quarter 2009), pp. 136-143; and Clark and Gunziger, *Winning the Airwaves*, pp. 19-21.

Footnote 139: This is why, when the Soviet Union learned of American advances with stealth technology, it started pursuing multi-static radars. See Director of Central Intelligence, *Special National Intelligence Estimate*, p. 6.

Footnote 140: See also Hanle, "Survey of Bistatic and Multistatic Radar," p. 592; Chernyak, *Fundamentals of Multisite Radar Systems*, pp. 9-10, 36 and 46; Nguyen and Ançay, *Signal Processing for Multistatic Radar Systems*, p. 3.

Footnote 144: As the project engineer behind the first stealth fighter, the F-117, put it, "the final 10 percent striving towards maximum perfection costs 40% of the total expenditure on most projects." Rich and Janos, *Skunk Works*, p. 325.

Footnote 145: Radar absorbing materials can be used both for the external structure of a vehicle (i.e., composite carbon-fibers) as well as for paint coating applied on the structure itself (e.g. "iron ball paint" or "neoprene paint"). See also Sang-Young Kim and Sung-Soo Kim, "Design of Radar Absorbing Structures Utilizing Carbon-Based Polymer Composites," *Polymers and Polymer Composite* Vol. 26 No. 1, (January 2018), pp. 105-110. For a less technical discussion, see Dan Katz, "The 'Magic' Behind Radar-Absorbing Materials for Stealthy Aircraft, *Aviation Week & Space Technology* (Oct 28, 2016).

Footnote 149: The reflectivity of an object depends on incident polarization, on the number of plies in the composite material, and on the fiber orientation. Radar reflectivity is minimized when the incident polarization is aligned with the fiber direction in unidirectional composites.

Footnote 153: See also Mark Denny, *Blip, Ping & Buzz: Making Sense of Radar and Sonar* (Baltimore, MD: The Johns Hopkins University Press, 2008), pp. 15-45.

Footnote 154: See also Price, *War in the Fourth Dimension.*

Footnote 155: See also Robert N. Lothes, Michael B. Szymanski Richard G. Wiley, *Radar Vulnerability to Jamming* (London, UK: Artech House Radar 1990); and Bryan Clark and Mark Gunzinger, *Winning the Airwaves: Regaining America's Dominance in The Electromagnetic Spectrum* (Washington, DC: Center for Budgetary and Strategic Assessment, 2015).

Footnote 157: This would mean imputing the unique radar return of a given drone platform into a library of signals so as to enhance the probability of detection; modulating the frequency, polarization and amplitude of the radar waves so as to overcome the attenuation of the RAM employed by enemy drones, or devising electronic counter-counter-systems so as to defeat the enemy drones' EW capabilities. Lynch, *Introduction to RF Stealth*, pp. 201-222; Shrader and Gregers-Hansen, "MTI Radar," pp. 2.1-2.91; and Sukharevsky (eds.), *Electromagnetic Wave Scattering by Aerial and Ground Radar Objects*, pp. xix and 91; and

Footnote 158: Siobàn O'Grady, "What is the Russian S-400 Air Defense System, and Why is the U.S. Upset Turkey Bought It?," *The Washington Post* (July 12, 2019); Snehesh Alex Philip, "Israeli F-35s hoodwinked S-300 system of Iran, but won't be a problem for India's S-400, *The Print* (July 3, 2019).

Footnote 162: High Energy Laser weapons propagation (and hence efficacy) is affected by many factors like diffraction, absorption, aerosol scattering, atmospheric turbulence, and by weather conditions (snow, fog, rain, and so on). Despite that, the main problem for HEL beam propagation is probably represented by atmospheric thermal blooming. Jean-François Daigle et al., "The

Importance of Thermal Blooming for Laser Weapon Atmospheric Propagation Modelling," in H. Hua et al. (eds.) *OSA Imaging and Applied Optics Congress 2021* (Optica Publishing Group, 2021), paper PTh2E.4.

Footnote 163: Andrew F. Krepinevich, *War Like No Other: Maritime Competition in a Mature Precision-Strike Regime* (Washington, DC: CSBA, 2014), pp. 3 and 10; Gunzinger and Clark, *Sustaining America's Precision Strike Advantage Regime*, pp 54-55; Mark Gunzinger and Bryan Clark, *Winning the Salvo Competition Rebalancing America's Air and Missile Defenses* (Washington, DC: CSBA, 2016), pp. 25-26; Carl Rehberg and Mark Gunzinger, *Air and Missile Defense At a Crossroads: New Concepts and Technologies to Defend America's Overseas Bases* (Washington, DC: CSBA, 2018), pp. 21-31.

Footnote 164: Valerie Insinna, "Coming in 2021: A laser weapon for fighter jets", *Defense News* (November 2017), https://www.defensenews.com/air/2017/11/07/coming-in-2021-a-laser-weapon-for-fighter-jets/; Jon Gambrell, "US Navy fires laser weapon in Mideast amid drone boat threat", *Navy Times* (December 2021), https://www.navytimes.com/news/your-navy/2021/12/15/us-navy-fires-laser-weapon-in-mideast-amid-drone-boat-threat/; Jared Keller, "The Air Force successfully tested a mobile laser weapon to protect convoys from enemy drones", *Task & Purpose* (September 2020), https://taskandpurpose.com/military-tech/air-force-laser-clws-force-protection/; Apoorva Jain, "Dogfighting, Stealth Jets Could Become Obsolete As US, China Look To Arm Their Fighter Jets With 'New-Age Weapons'", *The Eurasian Times* (August 2021), https://eurasiantimes.com/dogfighting-stealth-jets-could-become-obsolete-as-us-china-look-to-arm-their-fighter-jets-with-new-age-weapons/; Gunzinger et al., *An Air Force for an Era of Great Power Competition*, p. 50.

Footnote 167: The Skyshield defense system consist of a fire control unit, radar, missile launchers and revolver guns. Two of its revolver guns can shot a barrage of 25 rounds of AHEAD ammunitions, which each shell contains 152 sub-projectiles, for a total of 3.800 sub-projectiles fired in within 0.7 seconds. See "Oerlikon Skyshield Ground-Based Short-Range Air Defense System, *Army Recognition* (February 18, 2018).

Footnote 168: The Pantsir-S1 carries up to twelve 57E6 or 57E6-E two-stage solid fuel radio-command-guided surface-to-air missiles in sealed ready-to-launch containers. According to some sources the Pantsir-S1 could be equipped with the Gvozd, a new armament designed to destroy small targets. According to them, the Pantsir will be able to carry 4 Gvozd in each of its canisters, for a total of 48 missiles. See Ben Brimelow, "Russia's newest anti-air defenses are in Syria — and the US should be worried", *Business Insider*, April 11, 2018.

Footnote 171: See also William G. Ballard and Stéphane Kemkemian, "Fire-Control Radar," in William L. Melvin and James A. Scheer (eds.), *Principles of Modern Radar Vol. III: Radar Applications* (Edison, NJ: SciTech Publishing, 2014), pp. 117-174.

Footnote 188: See also Ashish Dangwal, "Ukraine Receives More 'Game Changing' Bayraktar TB2 UAVs; Kyiv Claims Turkish Drones Inflicting Heavy Damage On Russia", *The Eurasian Times*, March 3, 2022, https://eurasiantimes.com/ukraine-receives-more-game-changing-bayraktar-tb2-uavs/.

Footnote 189: See also "Kiev loses 30 drones in attempt to seize Snake Island - Russian Defense Ministry," *TASS* (May 10, 2022), https://tass.com/defense/1449051?utm_source=google.com&utm_medium=organic&utm_campaign=google.com&utm_referrer=google.com.

Footnote 191: The same pilot added that "My opinion is knowing the Russian air defense right now, and knowing that range of the missiles that Gray Eagle, I'll give you a 90% chance that it will be shot down." Cited in Valerie Insinna, "US-made jets, air defense on Ukrainian fighter pilots' wishlist, but not Gray Eagle," *Breaking Defense* (June 22, 2022), https://breakingdefense.com/2022/06/us-made-jets-air-defense-on-ukrainian-fighter-pilots-wishlist-but-not-grey-eagle/. Commenting on this news, two aviation journalists noted that "In this regard, it's worth noting that the U.S. Army has reached many of the same conclusions about the MQ-1C's ability to survive even in environments with relatively limited threats. The U.S. Air Force has been looking to move away from the MQ-9 Reaper, the Gray Eagle's larger cousin, for the same reasons. Both services, together with General Atomics, are now exploring various new concepts of operation that would allow these unmanned aircraft to continue to play useful roles in future higher-end conflicts…" Joseph Trevithick and Oliver Parken, "Ukrainian Fighter Pilots Call B.S. On Need For Gray Eagle Drones," *The Drive – The Warzone* (June 22, 2022), https://www.thedrive.com/the-war-zone/ukrainian-fighter-pilots-call-bullshit-on-need-for-mq-1c-gray-eagle-drones.