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A "System of Systems" Approach to Countering Drones
Examining Recent Operations from the Middle East to Ukraine

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Two Ukraine-owned and operated Bayraktar TB2 combat drones armed with MAM-L laser-guided bombs. Shutterstock

Since the end of the Cold War, the U.S. military has counted on air superiority in its conflicts, an expectation reinforced by experiences in the Persian Gulf, the Balkans, Afghanistan, and Iraq. But in the past decade, the operational environment has changed with the proliferation of drones—aka unmanned aerial vehicles (UAVs)[1]—among America's state and nonstate adversaries. Drones offer a cheap, effective precision-strike capability, obviating the need for a large, modern air force. Commenting on this "inflection point" in aerial warfare, then U.S. Central Command head Gen. Kenneth F. McKenzie Jr. testified as follows in April 2021 before a U.S. congressional committee: "For the first time since the Korean War, we are operating without complete air superiority...Until we are able to develop and field a networked capability to detect and defeat [drones], the advantage will remain with the attacker."[2]

> **“For the first time since the Korean War, we are operating without complete air superiority”**
>
> –Gen. Kenneth F. McKenzie, former commander, U.S. Central Command

To address this growing challenge, the United States and other countries have begun investing in counter-drone systems, or counter–unmanned aerial systems (C-UAS). These may use radar, electro-optical/infrared (EO/IR), acoustic, or radio frequency sensors to detect a drone’s physical, visual, thermal, audible, or electromagnetic signatures.[3] Once detected, the drone may be engaged via kinetic means (missiles, other drones, guns, and nets) or nonkinetic means, with the latter encompassing the use of electronic warfare (EW), hacking, or directed-energy pulses to jam, seize control of, or disable the drone. Alternatively, attacks can target other elements supporting a drone system.

This paper reviews counter-drone systems and methods used in recent conflicts in Syria, Yemen, Libya, Nagorno-Karabakh, and Ukraine. In some cases, such as in Libya and Nagorno-Karabakh, combat drones had strategic effects, either halting major advances or contributing significantly to victories, while in other conflicts, such as in Ukraine, reconnaissance drones served as force multipliers, operating in support of ground forces. Nevertheless, most U.S., Turkish, Russian, and Chinese drones in question—as well as homemade drones operated by nonstate actors like the Islamic State—were downed, with claimed interception rates of 80 percent, 90 percent, and in some cases nearly 100 percent. And the interceptions were achieved not by emerging, dedicated counter-drone systems, but by legacy air defense and EW systems, including a hodgepodge of Soviet-era air defenses. In the Ukraine context, more modern NATO systems have also been put to use.

Counter-drone efforts were most successful when defenses were layered, providing multiple opportunities to intercept drones in flight, and early warning, ground-based air defenses, EW assets, and combat aircraft functioned in an integrated fashion. Moreover, the use of newer, more capable drones or defenses—often acquired abroad—significantly affected battlefield dynamics, especially in Libya and Ukraine.

Abbreviations

AAM	air-to-air missile
AEW&C	airborne early warning and control
C-UAS	counter–unmanned aerial system
EO/IR	electro-optical/infrared
EW	electronic warfare
GNA	Government of National Accord (Libya)
LNA	Libyan National Army
MANPADS	man-portable air defense systems
NASAMS	national advanced surface-to-air missile system
SAM	surface-to-air missile
SEAD/ DEAD	suppression and destruction of enemy air defense
SPAAG	self-propelled antiaircraft gun
UAS	unmanned aerial system
UAV	unmanned aerial vehicle

Syria, 2011–

The Syrian conflict evolved from a civil war to a regional struggle that drew in a number of external powers. Russian forces, which in 2015 intervened in support of the Bashar al-Assad regime, were the main operators of drones and counter-drone systems in Syria. This section will largely focus on their experiences, though it will also mention Turkish operations in northwest Syria.

Russia's main operational hub in Syria was located at Hmeimim Air Base, where it deployed an air defense array comprising short-, medium-, and long-range surface-to-air missile (SAM) systems and EW assets.[4] After Russia established a separate, counter-drone command post in Syria in late 2017 and integrated its early warning radars, SAMs, and EW,[5] Russian defenses at Hmeimim and Tartus enjoyed significant success against jihadist and Syrian opposition drone attacks.[6] Russian ground-based defenses also enjoyed some success against Turkish drones operating in Syria's Idlib province.[7]

Russian and Syrian Pantsir-S1 systems that operated independently, however, often did not fare well against Turkish drones in northern Syria, perhaps after being blinded by Turkish EW attacks.[8] Some of the Syrian Pantsirs that were destroyed may have been inferior export models and were operated by less-than-proficient Syrian crews, making them susceptible to Turkey's use of offensive EW.[9] Russia also reportedly lost scores of Russian Orlan-10 reconnaissance drones to Turkish air defenses and Syrian rebel forces.[10]

EW proved particularly crucial for both Russian and Turkish counter-drone operations. Russia's Krasukha-4 mobile EW system disabled communications of drones and combat drones operating at low and medium altitudes, reportedly at ranges of more than 150 kilometers.[11] Turkey's Koral EW system reportedly supported Turkish drones conducting suppression and destruction of enemy air defenses (SEAD/DEAD) operations in northern Syria, from across the border in Turkey.[12] The Koral was likely responsible for Turkey's ability to operate its drones undetected within the engagement zones of Syrian Pantsir systems, in effect allowing Turkey to deploy its drones as a conventional air force, conducting air-to-air and air-to-ground strikes in northern Syria.[13]

Air-to-air engagements accounted for the destruction of smaller numbers of drones. Syrian aircraft downed Jordanian drones with air-to-air missiles in June 2017 but were less effective operating against Turkish drones in northern Syria.[14] Turkey supported its drone operations from across the border with its Boeing E-7T Peace Eagle airborne early warning and control (AEW&C) aircraft, directing F-16s to launch missiles beyond visual range at Syrian Sukhoi-24 attack aircraft attempting to intercept Turkish drones and combat drones over northern Syria.[15]

Overall, from 2018 to 2020, Russian defenses in Syria reportedly disabled more than 150 drones.[16] Russia's experience defending Hmeimim Air Base has heavily influenced its current counter-drone concept of operations and provided the foundation for counter-drone training across the Russian military, at the platoon, company, battalion, and brigade level.[17] Beginning in 2019, all major Russian military exercises are said to have featured drills simulating attacks by drone swarms, with EW functioning as a key element.[18] Logisticians, maintainers, and even cooks are being trained in counter-drone tactics, and counter-drone training is now mandatory in all Russian military services.[19]

Saudi Arabia, Yemen, 2015–

During the Yemen conflict, Saudi Arabia has accumulated extensive experience—albeit at a high price[20]—defending its long borders and geographically dispersed industrial targets and population centers against drone strikes.[21] The Houthis have relied heavily on drones in their attacks on Saudi Arabia—since 2021, nearly two-thirds of their attacks have involved drones[22]—and have mainly employed the Qasef-1/2K and Sammad-1/2/3 family of drones supplied by Iran.

With a focused effort to counter the threat, Saudi Arabia claimed a drone intercept rate of 90 percent,[23] the result of its integration of low-level ground radars, airborne early warning aircraft, and F-15 fighters. The Royal Saudi Air Force is one of only three countries in the Middle East possessing AEW&C aircraft, operating a squadron of five U.S.-made Boeing E-3A Sentry and two Saab 2000 Erieye AEW&C aircraft.[24] Further, in February 2020, Britain deployed mobile Saab Giraffe radars to Saudi Arabia, which provide a 360-degree networked air picture.[25] France has reportedly provided further coverage via unspecified radars from Thales Group (possibly Ground Master).[26] Saudi Air Force F-15s armed with advanced air-to-air missiles and radars capable of detecting small drones provided an effective but costly solution to addressing the drone threat.[27]

The Houthis use an assortment of SAM systems for drone defense, including converted R-27 air-to-air missiles and man-portable air defense systems (MANPADS) that previously belonged to the Yemeni Air Force, as well as Iranian Misagh-2 shoulder-launched SAMs.[28] By the end of 2015 alone, the Houthis had successfully shot down as many as twelve coalition drones.[29] They have since downed several U.S.-made combat drones, including MQ-9B Reapers, using SAMs.

One notable Saudi failure came on September 14, 2019, when Iran launched eighteen drones and seven cruise missiles at Saudi Aramco's Abqaiq and Khurais oil processing plants, knocking out half of the country's daily crude oil production and 5 percent of global daily production.[30] Saudi-operated Patriot SAMs tasked with protecting the sites reportedly failed to engage the incoming

Royal Saudi Air Force F-15SAs.

Debris from Iranian cruise missiles and Shahed-131 kamikaze drones used to attack Saudi Aramco oil facilities on display at a news conference in Riyadh, September 18, 2019. REUTERS/Hamad I Mohammed

drones[31]—although the Patriot was never designed to counter small, maneuverable drones flying at low altitudes.[32] Further, Patriot radars are reported to have a relatively narrow 120-degree field of view, requiring them to be oriented in the anticipated direction of attack to respond effectively.[33] Given that most missile and drone attacks since the conflict began in 2015 emanated from the south, Saudi Patriot batteries were oriented accordingly,[34] and the Patriot radars were therefore unable to recognize and respond to an attack coming from the northeast.

This shortcoming was addressed weeks later by the transfer of four U.S. AN/MPQ-64 Sentinel radars, and the aforementioned French and British radar systems, to bolster defenses against cruise missiles and drones by providing 360-degree coverage.[35] The United States and Saudi Arabia have since conducted joint counter-drone exercises, mainly out of Prince Sultan Air Base near Riyadh.[36] Further, in March 2023, the United States and Saudi Arabia completed their first joint counter-drone exercise at the newly created Red Sands Integrated Experimentation Center, a regional training site established in the kingdom to test new and existing counter-drone technologies.[37]

Libya, 2014–

In 2019, UN Special Representative to Libya Ghassan Salamé called the Libyan conflict the "largest drone war...in the world," with more than a thousand airstrikes conducted by drones since the conflict began in 2014.[38] Both sides used foreign-supplied and operated drones and air defenses, with the Government of National Accord (GNA) relying mainly on the Turkish-supplied and operated Bayraktar TB2 and the Libyan National Army (LNA) fielding mainly the Chinese-built, UAE-supplied and operated Wing Loong I/II.[39] Both sides also used commercial mini-drones for reconnaissance, but these ultimately proved unreliable and susceptible to jamming.[40]

Overall, counter-drone operations produced relatively high drone attrition rates in Libya. Chinese-made Wing Loong I/II drones and Russian-made Pantsir-S1 SAM systems—provided by the UAE in 2016 and 2019, respectively[41]—gave the LNA a significant tactical advantage over the GNA.[42] By September 2019, the LNA had virtually eradicated GNA-operated Turkish drones, and the GNA's largely inferior antiaircraft guns and shoulder-fired MANPADS were downing only some LNA drones.[43] By January 2020, however, nine months after the LNA offensive on Tripoli began, Turkey had deployed a layered,[44] integrated defense at the GNA's Misratah and Mitiga Air Bases, allowing the GNA to consistently shoot down LNA drones over areas it controlled in northwest Libya.[45]

The GNA's ground-based defenses included Turkish-supplied HAWK and Hisar SAM systems and Korkut self-propelled antiaircraft gun systems.[46] Turkey also deployed land-, sea-, and air-based radar and early warning systems. On land, the GNA deployed AN/MPQ-64 Sentinel 360-degree, phased array radars.[47] At sea, Turkish Gabya-class frigates provided the GNA with early warning using AN/SPS-49 long-range air surveillance radars.[48] In the air, Turkey used AEW&C aircraft like Boeing E-7T Peace Eagles flying off the coast of Tripoli.[49] For EW, in early 2020 Turkey deployed its Koral system to Mitiga Air Base,[50] which was not only capable of disrupting Emirati Wing Loong operations but also proved effective again at disrupting and targeting Pantsir SAM systems.[51] The GNA also incorporated Turkish-manufactured STM Kargu-2 rotary wing autonomous loitering munitions to hunt down logistics convoys and retreating LNA units.[52] While the UN experts panel claimed that the Kargu-2 is a truly autonomous system, STM claims that a human operator always remains in the loop.[53]

The LNA's main ground-based point defense system used to counter drones included the Russian Pantsir-S1, reportedly operated by crews of Russian Wagner Group mercenaries and poorly trained

In Libya, debris from a downed UAE-owned and operated Chinese Wing Loong II combat drone.

Libyans.[54] From November 2019 to March 2020, the LNA claimed its Pantsir systems shot down at least sixteen Turkish aircraft and were overall responsible for destroying more than half of the total two dozen Turkish drones shot down in Libya.[55]

Despite initial successes, however, Pantsirs deployed to Libya—like those in Syria—proved vulnerable to Turkish EW and Bayraktar TB2s firing MAM-L and MAM-C laser-guided bombs.[56] Pantsirs were often struck not only while active on the battlefield but also while nonoperational, such as when parked in hangars or in transit on flatbed trucks.[57] This demonstrates a key advantage of the persistent-targeting capability of drones, which can loiter over the battlefield and attack their targets when most vulnerable. Pantsirs were also occasionally overwhelmed, as Turkey sometimes attacked with half a dozen or more drones simultaneously.[58] On several occasions, Pantsir-S1s failed to engage Turkish drones and, in at least one case, was observed with its radar array spinning—indicating that it was turned on—right before being destroyed.[59] By the end of May 2020, Pantsir crews improved their defense somewhat by switching to passive electro-optical sensors, thus limiting their vulnerability to jamming by Koral EW systems.[60]

Nagorno-Karabakh, September–November 2020

During the Nagorno-Karabakh conflict in 2020, Azerbaijan used Turkish-made Bayraktar TB2 combat drones and Israeli-made Harop loitering munitions to defeat virtually every layer of Armenia's dense air defenses in the theater of operation.[61] Azerbaijani drones repeatedly destroyed Armenian ground-based air defenses,[62] often deployed in the open, without camouflage or other defensive measures.[63] Overall, Azerbaijan destroyed 65 percent of Armenia's air defense systems deployed in Nagorno-Karabakh.[64] In comparison,[65] Armenia shot down only two TB2s during the entire conflict.[66] Manned multi-role fighter aircraft were largely absent from the skies, allowing drones to operate unhindered.[67]

Azerbaijan also converted Soviet-era Antonov-2 biplanes into remotely piloted aircraft and sent them into Armenian air defense engagement zones as decoys.[68] Once the Armenian SAMs activated and engaged the biplanes, Azerbaijani Harops, loitering above, used their EO/IR sensors to locate Armenian radars and destroy them via kamikaze attack.[69] Bayraktar TB2s relayed targeting data to Azerbaijani artillery and/or dropped laser-guided bombs to destroy Armenian systems.[70] Azerbaijan has not publicly acknowledged using EW in Nagorno-Karabakh. However, as in the Syrian and Libyan theaters, Azerbaijani TB2s destroyed several Armenian air defense systems while their radars were operating, hinting at the combined use of EW and drones.[71]

Armenia's ground-based air defenses consisted mostly of obsolete Soviet-era mobile SAM systems,[72] mainly SA-8s,[73] that proved less capable than more modern Russian systems deployed to Syria. Collectively, Armenian systems were consistently unable to detect, track, and target Azerbaijani drones.[74] SA-10s and SA-11s in Armenian service lacked the ability to network dispersed radars to produce a single operating picture.[75] Systems like the SA-4, SA-6, SA-8, and SA-13 were reportedly able to detect Azerbaijani drones but unable to intercept them,[76] and were vulnerable to enemy EW.[77] Armenian SA-11 and SA-15 SAMs and MANPADS downed a few Azerbaijani drones but were introduced too late in the conflict to have a significant impact.[78] Armenian self-propelled antiaircraft guns such as the ZSU-23-4 Shilka, or MT-LB vehicles equipped with antiaircraft guns, were largely ineffective without upgraded radars and EO sights.[79]

Armenia's Russian-supplied Pole-21 EW systems proved very effective at disrupting Azerbaijani drones when used.[80] Armenia possessed one mobile Repellent EW complex, but according to Prime Minister Nikol Pashinyan, it did not work and was destroyed in combat.[81] In northwest Armenia, Russia deployed the Krasukha mobile EW system at its own

A Turkish Bayraktar TB2 combat drone armed with MAM-L laser-guided bombs, September 27, 2021. Credit: Oryx

military base in Gyumri. Some reports claim the Krasukha downed at least nine Bayraktar TB2s,[82] although given that Gyumri is roughly 250 kilometers from the main battlefield and thus possibly outside the Krasukha's effective range, it is unclear whether these claims are credible.

Ukraine, February 2022–

Ukraine's drone defenses in its war against Russia consist largely of three layers: fighter jets armed with air-to-air missiles; ground-based air defenses, including SAMs and antiaircraft guns; and soldiers armed with MANPADS and heavy machine guns. Before the war, Ukraine's inventory consisted almost exclusively of Soviet-era ground-based air defense systems, similar to those used in Syria, Libya, and Nagorno-Karabakh. Over time, with the infusion of advanced Western air defense systems, such as the national advanced surface-to-air missile system (NASAMS), IRIS-T SLM, Vampire, Avenger, Stinger, and Gepard, Ukraine built a more effective and extensive layered, integrated air defense architecture.[83] Based on published estimates of destroyed equipment,[84] Ukraine has so far proved increasingly adept at downing Russian combat drones,[85] while Russian EW systems are reportedly downing thousands of Ukrainian drones a month—the bulk of which are likely expendable commercial reconnaissance drones.[86]

Ukrainian forces have operated Turkish-supplied Bayraktar TB2 combat drones and smaller reconnaissance drones, whereas Russian forces have mainly employed the Russian Orlan-10 reconnaissance drone, Lancet-1/3 loitering munition, and Iranian Shahed-131/136 (Russian name: Geran-1/2) one-way attack drone, the last of these introduced six months after the invasion. Both sides use loitering munitions, with varying degrees of effectiveness,[87] and thousands of cheap, expendable, commercial quadcopter drones, mainly the Chinese-made DJI Mavic, for a variety of roles such as reconnaissance, artillery spotting, and bombing.[88] Commercial quadcopters have also reportedly been used to knock enemy quadcopters out of the sky.[89]

In the first few months of the invasion, Ukrainian TB2s destroyed scores of Russian military vehicles and equipment moving in columns on roads,[90] while Ukrainian ground forces downed or disabled at least forty-five Russian Orlan-10 reconnaissance drones.[91]

Notably, published images of downed Orlan-10s showed that most were intact, suggesting the use of EW rather than kinetic means.[92]

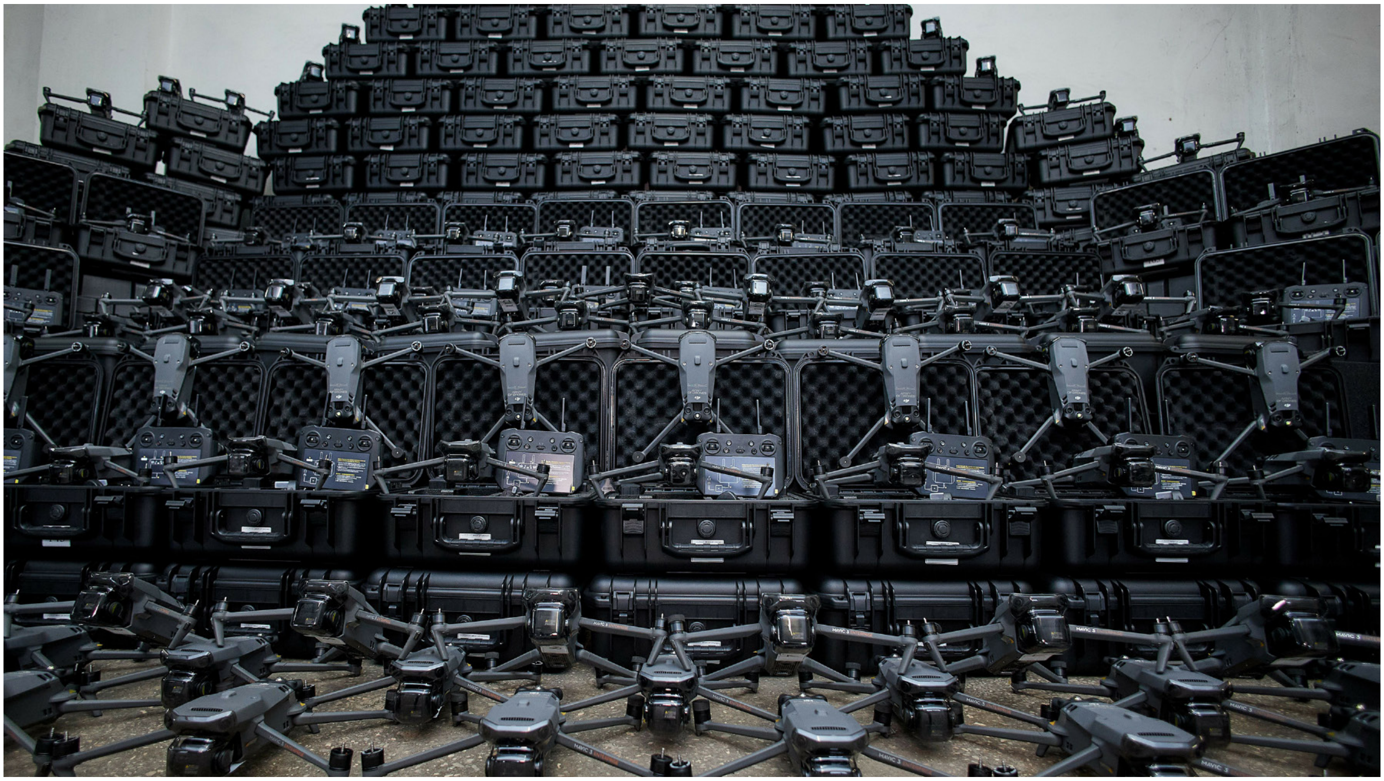
Russian forces reportedly shot down the first TB2 in mid-March 2022,[93] and in the first five months of the war, reportedly destroyed around 90 percent of all Ukrainian drones sent their way.[94] They also made effective use of EW to track and neutralize Ukrainian drones. On average, Ukrainian drones, from commercial quadcopters to larger fixed-wing models,[95] reportedly had a dismal life expectancy of three and six flights, respectively.[96] By summer 2022, Russia had dug into areas of eastern Ukraine and effectively integrated early warning radars,[97] ground-based air defenses, and EW to identify, disrupt, and disable Ukrainian drones.[98] According to one Ukrainian pilot, the Bayraktar TB2 became "almost useless" with the increased integration of Russian defenses, requiring Ukrainian pilots to use the TB2 more selectively for special operations.[99]

Yet Russia's Repellent EW system was, as in Armenia, largely ineffective.[100] More capable Russian EW systems, like the Krasukha, which jam and disrupt the radar and communication links of TB2s, have at times been equally disruptive to Russia's own troops and equipment.[101] Short-range R-330Zh Zhitel EW systems have also been effective at jamming the GPS signals that the TB2s and DJI Mavics depend on for navigation.[102]

Russian forces also effectively used Orlan-10 drones with tactics similar to those used by Azerbaijani forces in Nagorno-Karabakh to perform SEAD/DEAD operations.[103] After flying into Ukrainian air defense engagement zones, causing Ukrainian SAMs to activate their fire control radars and thereby reveal their location, Orlan-10s suppressed the exposed systems using EW and relayed targeting coordinates to Russian artillery to enable their destruction.[104] This forced Ukraine's short-to-medium-range SAM systems such as the SA-8 and SA-11 to withdraw further behind the frontlines to cut their losses.[105]

For Ukraine, Western ground-based air defenses have proven key to improving drone interception rates. Ukrainian forces claim that German-supplied IRIS-T SLM heat-seeking missiles have shot down every projectile they have faced since being deployed

In Ukraine, debris from a Russian Lancet kamikaze drone that exploded prematurely after failing to penetrate protective chain-link fencing around a Ukrainian AHS Krab self-propelled howitzer artillery gun, January 2023. Credit: Kriegsforscher



Dozens of DJI Mavic 3T reconnaissance drones delivered to the Ukrainian military, March 2023. Credit: Mykhailo Fedorov

in October 2022, while according to U.S. defense secretary Lloyd Austin, American-supplied NASAMS have had a "100 percent success rate" in Ukraine.[106] The United States likely supplied Ukraine with the NASAMS-2 variant, which is equipped with the NATO standard Link-16 communications system,[107] making the NASAMS interoperable with other SAMs such as the U.S. Patriot and German IRIS-T SLM.[108] When properly integrated, sensors from one system, including aircraft flying outside Ukrainian airspace,[109] can provide targeting data to enable another system to intercept.

According to Ukraine's defense attaché to the United States, Maj. Gen. Borys Kremenetsky, German-supplied Gepard self-propelled antiaircraft guns, as well as ZSU-23-4s and SA-8s, have been "successful" against drones.[110] An analysis by Britain's Royal United Services Institute also claimed that the Gepard is highly effective, while Soviet-era SA-19s and the ZSU-23-4s struggle to shoot down Iranian Shahed-136 drones.[111] Ukraine also deployed MANPADS across its units and used them effectively against Shahed-136 drones, as well as against Russian aircraft operating at low altitudes.[112] The most common MANPAD deployed by Ukrainian forces is the SA-18, but they now also possess an assortment of Western-supplied MANPADS including the American Stinger, British Martlet and StarStreak, French Mistral, and Polish Piorun.[113]

During the conflict, Ukraine has claimed climbing interception rates of Iranian Shahed-136 drones, from 70 percent in October 2022 to 100 percent by January 2023.[114] And Western actors are taking steps to ensure Ukraine keeps its advantage. Shortly after the United States pledged to supply Ukraine with a Patriot missile battery on December 21, 2022,[115] sixty-five handpicked Ukrainian soldiers began training at Fort Sill, Oklahoma.[116] The first U.S.-supplied Patriot battery arrived in Ukraine on April 19, 2023,[117] and was immediately put to use. In addition, Germany has pledged to supply Ukraine with one Patriot missile battery and the Netherlands with two.[118]

Conclusion

There is no counter-drone silver bullet. The most effective defense against drones at this time consists of layered, integrated, interoperable systems capable of providing 360-degree coverage, employing a variety of hard- and soft-kill solutions, such as antiaircraft artillery, surface-to-air and air-to-air missile interceptors, and EW systems.

Maj. Gen. Sean Gainey, the outgoing director of the U.S. Army's new Joint Counter–small Unmanned Aircraft Systems Office (JCO), describes a "system-of-systems, layered approach to a common command-and-control method" as the "best way" to counter drones, adding that there is "no one capability that will defeat the range of [drone] threats" on today's battlefield.[119]

The experiences of drone operators in other conflicts have generally confirmed these findings. For instance, Israel has downed a number of drones using a variety of hard- and soft-kill systems. In March 2021, Israeli F-35I fighters shot down two Iranian Shahed-197 drones over neighboring countries—one approaching from the south and one from the east[120]—in coordination with these states before they could enter Israeli airspace. In July 2022, Israel shot down three Hezbollah drones approaching offshore gas rigs by the Karish natural gas field in the East Mediterranean using F-16 fighters and Barak 8 surface-to-air missiles fired from the INS *Eilat*.[121] And in March 2023, Israel shot down a Hamas drone over Gaza using Iron Dome interceptors.[122]

Many of the most successful counter-drone cases outlined in this paper, however, involved the defense of point targets such as military bases. Units and facilities outside the umbrella provided by integrated defenses remain more vulnerable—at least for now. Further, no actors involved in the conflicts discussed were reported to have used dedicated counter-drone systems, relying instead mostly on legacy air defense platforms designed to shoot down ballistic missiles and conventional aircraft. While these systems can provide an adequate defense against large drones, they are ultimately too expensive to use against larger numbers of smaller drones.

In contrast, the U.S. military has already fielded several dedicated counter-drone platforms across its services, like Coyote and L-MADIS, with a number of additional prototypes undergoing operational testing in the field, like HELIOS. Israel's Drone Dome, a counter-drone system capable of using hard- and soft-kill solutions to neutralize a variety of drones, is already in use in several NATO and Asian countries (see appendix).[123] These systems present an opportunity to augment and complement existing legacy air defense systems, helping to fill the counter-drone capabilities gap while lowering the cost of interception.

With sufficient density and integration, interception rates of 80, 90, or at times nearly 100 percent can be achieved using existing technologies. But unmanned systems will likely continue to proliferate at an accelerating rate in the coming decades. If the United States is to maintain its battlefield advantage, whether against near-peer rivals or others, continued investment, testing, and fielding of counter-drone platforms will be paramount. In a February 2021 public address, General McKenzie highlighted the urgency of the situation, stating, "The growing threat posed by these systems [commercially available small drones] coupled with our lack of dependable, networked capabilities to counter them is the most concerning tactical development since the rise of the improvised explosive device in Iraq."[124]

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> –Gen. McKenzie

In fiscal year 2022/23, the U.S. Department of Defense plans to spend more than $668 million on counter-drone research and development and at least $78 million on counter-drone procurement.[125] Today, the JCO is looking to field directed-energy systems and high-powered microwave systems to disable drones, especially as adversary drones have become increasingly autonomous and resistant to EW. The JCO still emphasizes, however, the need to "have a kinetic solution" in case soft-kill solutions fail.[126] The continued search for effective responses to this threat will likely define the future of counter-drone warfare for years to come. ❖

The L-MADIS system (circled) was used to down an Iranian drone while parked on the bow of the USS Boxer *(LHD-4) as the ship transited the Strait of Hormuz, July 18, 2019. Credit: U.S. Marine Corps*

Appendix: Select Counter-Drone Systems

System	Description	Select Users	
SURFACE-TO-AIR MISSILES (SAMS)			
Hisar	Turkish-made, vehicle-mounted, heat-seeking SAM system with a reported engagement range of 10–20 km.	Turkey	
IRIS-T SLM (surface-launched missile)	German-made, vehicle-mounted, heat-seeking SAM system with a reported engagement range of up to 40 km.	Ukraine	
M1097 AN/TWQ-1 Avenger	U.S.-made, vehicle-mounted, heat-seeking SAM system based on the FIM-92 Stinger missile, with a reported engagement range of 4 km.	Saudi Arabia Ukraine	
MIM-23B improved homing-all-the-way killer (I-HAWK)	U.S.-made, towed, radar-guided SAM system with a reported engagement range of 25–35 km.	Saudi Arabia Turkey Ukraine	
MIM-104 Patriot	U.S.-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 70 km.	Saudi Arabia Ukraine	

System	Description	Select Users	
SURFACE-TO-AIR MISSILES (SAMS) *(Continued)*			
National advanced surface-to-air missile system (NASAMS)	U.S./Norwegian-made, fixed or vehicle-mounted radar-guided SAM system with a reported engagement range of 40 km.	Ukraine	
SA-3 Goa (S-125 Neva/ Pechora)	Russian-made, fixed, radar-guided SAM system with a reported engagement range of 25–35 km.	Armenia Azerbaijan Houthis Syria Russia Ukraine	
SA-4 Ganef (2K11 Krug)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 55 km.	Armenia Azerbaijan Syria Ukraine	
SA-6 Gainful (2K12 Kub)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of up to 25 km.	Armenia Houthis Syria Russia Ukraine	
SA-8 Gecko (9K33 Osa)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 15 km.	Armenia Azerbaijan Russia Syria Ukraine	

System	Description	Select Users	
SURFACE-TO-AIR MISSILES (SAMS) ***(Continued)***			
SA-10 Grumble (S-300P/PS/PT)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 50–75 km.	Armenia Russia Ukraine	
SA-11 Gadfly (9K37 Buk-M1)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 35 km.	Armenia Azerbaijan Russia Ukraine	
SA-13 Gopher (9K35 Strela-10)	Russian-made, vehicle-mounted, heat-seeking SAM system with a reported engagement range of 5 km.	Armenia Azerbaijan Russia Syria Ukraine	
SA-15 Gauntlet (9K330 Tor-M)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 10–15 km.	Armenia Azerbaijan Russia Syria Ukraine	
SA-17 Grizzly (9K317 Buk-M2E)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 35–50 km.	Azerbaijan Russia Syria Ukraine	

System	Description	Select Users	
SURFACE-TO-AIR MISSILES (SAMS) ***(Continued)***			
SA-19 Grison (2K22 Tunguska)	Russian-made, vehicle-mounted, self-propelled antiaircraft gun (SPAAG) and SAM system with a reported engagement range of 4 km for the guns and 20 km for the missiles.	Russia Ukraine	
SA-21 Growler (S-400 Triumph)	Russian-made, vehicle-mounted, radar-guided SAM system with a reported engagement range of 250 km.	Russia	
SA-22 Greyhound (Pantsir-S1)	Russian-made, vehicle-mounted, SPAAG and SAM system with a reported engagement range of 4 km for the guns and 20 km for the missiles.	LNA Russia Syria	
MAN-PORTABLE AIR DEFENSE SYSTEMS (MANPADS)			
FIM-92 Stinger	U.S.-made, shoulder-launched, heat-seeking missile system with a reported engagement range of 4–8 km. Can also be fired from the M1097 Avenger system.	GNA Saudi Arabia Turkey Ukraine	
Martlet	UK-made, shoulder-launched, laser-guided surface-to-air, surface-to-surface, and air-to-surface missile system with a reported engagement range of 8 km.	Ukraine	

System	Description	Select Users	
MAN-PORTABLE AIR DEFENSE SYSTEMS (MANPADS) ***(Continued)***			
Misagh-2	Iranian-made, shoulder-launched, heat-seeking missile system with a reported engagement range of 3–6 km.	Houthis	
Mistral	French-made, shoulder-launched or vehicle-mounted heat-seeking missile system with a reported engagement range of 3–6 km.	Ukraine	
Piorun	Polish-made, shoulder-launched, heat-seeking missile system with a reported engagement range of 4–6 km.	Ukraine	
SA-18 Grouse (9K38 Igla)	Soviet-made, shoulder-launched, heat-seeking missile system with a reported engagement range of 2–5 km.	Armenia Azerbaijan Russia Ukraine	
StarStreak	UK-made, shoulder-launched or vehicle-mounted laser-guided missile system with a reported engagement range of 5–6 km.	Ukraine	

System	Description	Select Users	
AIR-TO-AIR MISSILES (AAMS)			
AIM-9X Sidewinder	U.S.-made, heat-seeking, air-to-air and surface-to-air missile launched from U.S. fighter aircraft and NASAMS ground systems.	Saudi Arabia Ukraine	
AIM-120C advanced medium-range air-to-air missile (AMRAAM)	U.S.-made, heat-seeking, air-to-air and surface-to-air missile launched from U.S. fighter aircraft and NASAMS ground systems.	Saudi Arabia Ukraine	
SELF-PROPELLED ANTIAIRCRAFT GUNS (SPAAGS)			
Gepard	German-made, vehicle-mounted, antiaircraft system with a reported engagement range of 5 km.	Ukraine	
Korkut	Turkish-made, vehicle-mounted, antiaircraft system with a reported engagement range of 4 km.	Turkey	
ZSU-23-4 Shilka	Russian-made, vehicle-mounted, antiaircraft system with a reported engagement range of 4 km.	Armenia Azerbaijan Russia Ukraine	

System	Description	Select Users	
AIRBORNE EARLY WARNING AND CONTROL AIRCRAFT (AEW&C)			
Boeing E-3A Sentry	U.S.-made early warning and control aircraft capable of detecting and tracking airborne threats at a reported range of up to 375 km.	Saudi Arabia	
Boeing E-7T Peace Eagle	U.S.-made, early warning and control aircraft capable of detecting and tracking airborne threats at a reported range of up to 320 km.	Turkey	
Saab 2000 Erieye	Swedish-made, early warning and control aircraft capable of detecting and tracking airborne threats at a reported range of up to 350 km.	Saudi Arabia	
ELECTRONIC WARFARE (EW) SYSTEMS			
Koral	Turkish-made, vehicle-mounted, electronic warfare system designed to jam and deceive enemy radar, with a reported effective range of 200 km.	Turkey	
Krasukha-4	Russian-made, vehicle-mounted, electronic warfare system designed to jam radar and radio frequencies, with a reported effective range of 150–300 km.	Russia	

System	Description	Select Users	
ELECTRONIC WARFARE (EW) SYSTEMS *(Continued)*			
Pole-21	Russian-made, fixed or vehicle-mounted electronic warfare system designed to disrupt positioning and guidance systems, with a reported effective range of 25 km.	Armenia Russia	
Repellent	Russian-made, vehicle-mounted, electronic warfare system designed to jam telecommunication and positioning systems, with a reported range of 30 km.	Armenia Russia	
ILLUSTRATIVE COUNTER-DRONE SYSTEMS			
Coyote unmanned aircraft system	U.S.-made, fixed or vehicle-mounted, radar-guided, counter-drone system using tube-launched interceptors to kinetically destroy drones, with a reported engagement range of 15 km. Reportedly used by U.S. forces in Syria.	United States	
Dronebuster	U.S.-made, fixed or man-portable, electronic warfare system designed to disrupt drone communication signals within line of sight. Reportedly used by military and law enforcement across the world.	United States	

System	Description	Select Users	
ILLUSTRATIVE COUNTER-DRONE SYSTEMS *(Continued)*			
Drone Dome	Israeli-made, fixed or vehicle mounted, counter-drone system employing sensors, jammers, and lasers, with a reported engagement range of 2 km. Reportedly used by a number of NATO and Asian countries.	Israel	
High-energy laser with integrated optical-dazzler and surveillance (HELIOS)	U.S.-made, fixed, 60–120 kilowatt-class directed-energy weapon system for use against fast attack boats and drones, with a reported engagement range of 8 km. Reportedly being tested with the U.S. Navy aboard the USS *Preble*.	United States	
High-energy laser weapon system (HELWS)	U.S.-made, fixed or vehicle-mounted, 15–50 kilowatt-class directed-energy weapon system for use against mortar bombs and drones, with a reported engagement range of 3 km. Reportedly used by U.S. forces in undisclosed locations overseas.	United States	
Light-marine air defense integrated system (L-MADIS)	U.S.-made, fixed or vehicle-mounted, multi-functional electronic warfare system designed to disrupt drone communication signals, with an undisclosed engagement range. Reportedly downed an Iranian drone in the Strait of Hormuz in 2019 while deployed aboard the USS *Boxer*.	United States	

Image sources: Shutterstock, Wikimedia, OE Data Integration Network (ODIN) Worldwide Equipment Guide

NOTES

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