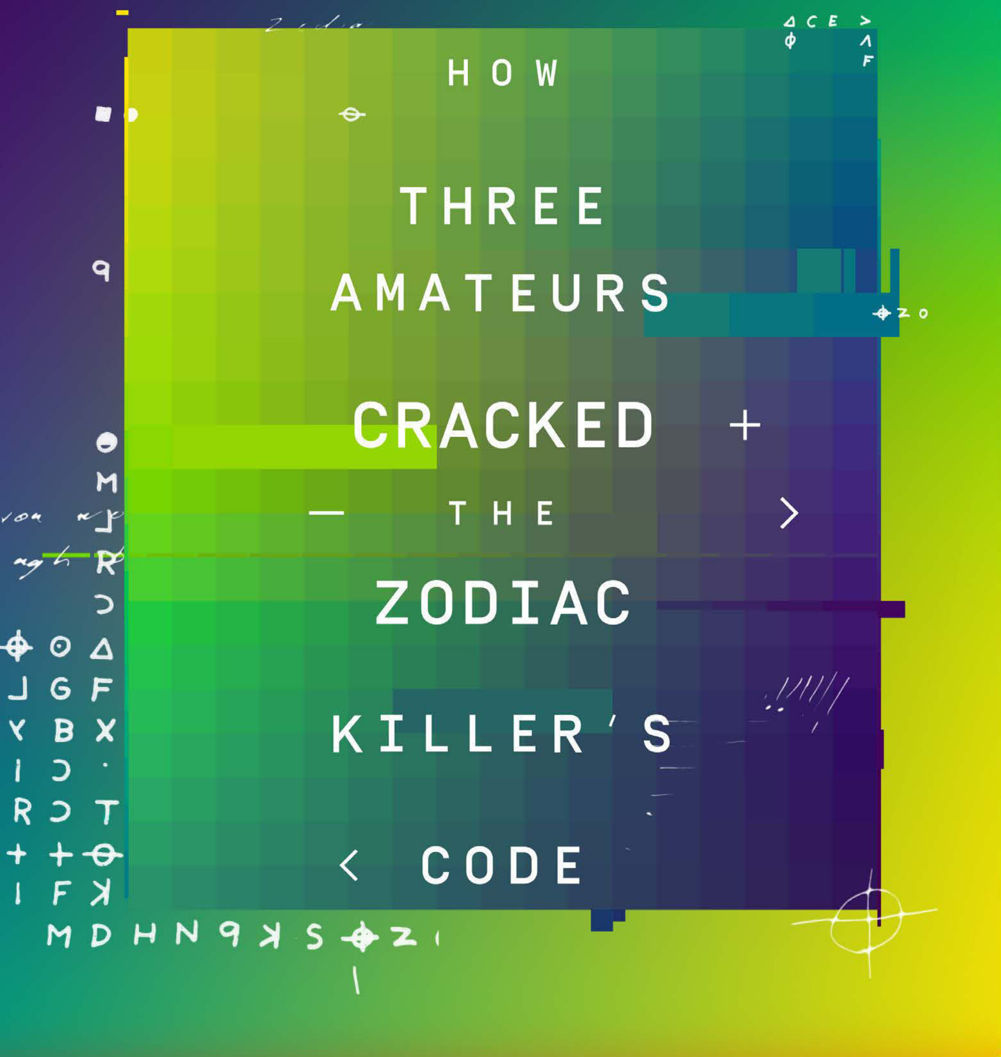
POPULAR MECHANICS



HOW THREE AMATEURS CRACKED THE ZODIAC KILLER'S CODE

PM

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August/September 2022

How three amateurs finally cracked the Zodiac Killer's code. **Plus:** The most powerful telescopes on earth—and beyond; everything we know about the Air Force's quest to build a hypersonic bomber; and more.

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Uncanny discoveries, insightful observations, ingenious hacks, and other prescient ideas from PopMech experts, contributors, and staff.

Writer: **Eric Adams**

Story: **These 17 Mega-Telescopes Are Making Mind-Bending Discoveries**

▶ Laying Eyes on a Galaxy

I'll never forget touring the Very Large Telescope in Chile and experiencing the southern hemisphere's night sky for the first time. I sat in a dark room for 20 minutes to allow my eyes to become dark-adapted, then I walked into what can only be described as a celestial wonderland. It was so clear that I saw actual galaxies—including the Large Magellanic Cloud and the Small Magellanic Cloud—and it struck me how much light pollution conceals from us. Light pollution has grown by a staggering 49 percent globally over the last 25 years, according to a 2021 British study, impacting both wildlife habitats and research sites like the telescopes featured in this issue.

Writer: **Hope Hodge Seck**

Story: **America's Most Fearsome Howitzer Has Entered the War in Ukraine**

▶ The Mobile Mortar Program That Could've Been

One of my favorite desk ornaments is a "tail feather" I received from a reporting assignment at Camp Lejeune, N.C. This five-pound hunk of brass and steel came from a Marine Corps 120mm towed mortar known as the Expeditionary Fire Support System. It held the charge assembly and propellant for the system's round. Marines liked the compact firepower of the EFSS, which, unlike the M777 howitzer in this issue, could fit inside a helicopter, but the Corps canceled the program in 2018 due to tech issues and budget demands. It reminds me that military needs don't exist in a vacuum; programs and specialties compete with each other for funding, and lots of good ideas end up on the chopping block.

Writer: **Kathryn Miles**

Story: **How Three Amateurs Finally Solved the Zodiac Killer's 340 Cipher**

▶ Liberate Investigators from Red Tape

I've spent the past five years investigating cold murder cases in the United States, and crowd-sourced solutions like those used to solve the 340 cipher excite me with their potential for innovative investigative tactics. In my reporting, I've often been dismayed by the number of self-induced impediments professional investigators encounter: Outdated methodologies, tunnel vision, and even outright bias can hamstring a case and lead investigators to an avoidable dead end. The work that resulted in a solution to the Zodiac cipher shows what happens when smart people have the freedom to explore novel approaches to old problems. I hope federal agencies take notice and allow their own experts similar latitude.

Writer: **Alex Hollings**

Story: **Inside Project Mayhem: America's Secret Plan to Develop a Hypersonic Bomber**

▶ America Almost Flew a Hypersonic Plane in the '50s

America's hypersonic history actually predates Sputnik. Boeing began its first hypersonic effort in 1957 with the X-20 Dyna-Soar. The 35-foot bomber would ride a rocket into the sky then separate and use its 20-foot wingspan to bounce along the earth's atmosphere at Mach 18, with the crew onboard delivering bombs or snapping pictures along the way. Boeing got as far as building a full-size mock-up of the bomber, with the modern equivalent of billions invested in the program. But when the Soviets launched Sputnik in October of that year, America divested from hypersonics to focus on the burgeoning space race.

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How These 17 Mega-Telescopes Make Mind-Bending Discoveries

If we're going to FaceTime with aliens, it will likely be through one of these badass instruments.

ERIC ADAMS

FEW SCIENTIFIC TOOLS ARE as productive, publicly revered, and seemingly infinitely capable as the humble observatory telescope. This optical marvel—found in locations ranging from the early Kitt Peak and Mt. Wilson observatories to Keck and La Silla, and now overhead as Hubble and Webb—aims massive mirrors and excruciatingly sensitive instruments around the heavens with the precision of a seasoned archer. The resulting imagery, whether it's an extraordinary first-ever look at a black hole or an intriguing first-time hint of a planet in a distant galaxy, captivates both the public and the scientists who dig into their prodigious data streams.

These world-class telescopes represent decades of innovative thinking, with clever design strategies and brilliant software solutions aimed at hunting down answers to cosmic queries. Though the astronomer peering thoughtfully into an eyepiece is a scenario from the past (data is processed digitally now), telescope forms remain broadly recognizable. Most use large mirrors to reflect light into sensors, and most sit on mountaintops high above the thicker atmosphere below. Their targets often define their sizes and configurations. "A bigger telescope collects more light and sees the universe at higher resolution than a small telescope, but if your goal is to detect X-rays from around a black hole, a small X-ray telescope is better than a large optical telescope," notes Rick Fienberg, a senior advisor to the American Astronomical Society. "If your goal is to observe a radio source at the highest possible resolution, you want to use a radio interferometer, which is a collection of smaller dishes spread out over an area much larger than anyone could build a single dish."

Modern telescopes also capitalize on the same steady technological progress that has rendered our own smartphones exceedingly capable. "When I was a grad student in the 1980s, a typical digital camera on a telescope had less than 100,000 pixels," Fienberg says. "The camera on the 8.4-meter telescope of the upcoming Vera Rubin Observatory has 3.2 billion pixels!" That's the largest digital camera ever built.

Among the dozens of superpowerful telescopes across the globe (and orbiting it), these are the biggest and best. We've assessed the capabilities and accomplishments of each, from so-called first light—their debut moments following construction—through today. As for the future? "The next big leap in technology is going to be very big, and it's coming soon—as in, by the end of this decade, when several huge telescopes will be coming online," Fienberg says. "The Giant Magellan Telescope and the Extremely Large Telescope are being built in Chile."

These mega-telescopes usually benefit from vast international partnerships, with participating governments and research organizations contributing to design, funding, and management in exchange for "time at the eyepiece" and the perpetual collaboration of some of the greatest minds in the known universe.

These are the instruments that keep astronomers up all night.

N°1 ‖ W.M. Keck Observatory

Manager: California Association for Research in Astronomy

First light: Keck I, November 24, 1990; Keck II, January 23, 1996

Location: Mauna Kea, Hawaii

Altitude: 13,796 feet

Mirror diameter: 10 meters each, comprising 36 hexagonal segments, each 6 feet across and 3 inches thick

The dual telescopes of the Keck Observatory—a gleaming pair of 98-foot-tall golf balls sitting atop a dormant volcano in Hawaii—were the first of the modern era of big-mirror telescopes. This was made possible by the introduction of active optics, which uses smaller mirror segments that are independently computer-aligned and adjusted, rather than trying to create a rigid single-piece mirror of the same size. (The latter would be too heavy to maintain its precise shape.) The telescopes can be used independently or in unison, operating as a single instrument with an aperture equivalent to their 280-foot combined width. Since their debut in the early 1990s, the pair have used their 10-meter mirrors to hunt planets around distant stars, explore the depths of black holes, and investigate the evolution of the universe.

N°2 ‖ Hubble Space Telescope [HST]

Manager: NASA/Space Telescope Science Institute

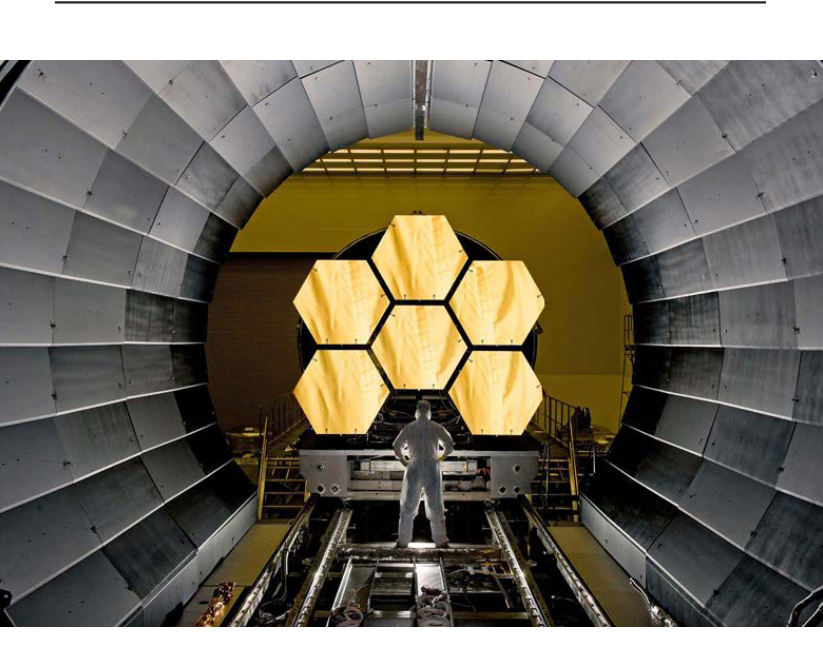
First light: May 20, 1990

Location: Low Earth orbit

Altitude: 333 miles

Mirror diameter: 2.4 meters

Though wildly expensive to build, space telescopes generate images unencumbered by the light pollution and atmospheric distortion that ground-based telescopes must deal with. Their images are pristine and detailed. Hubble is the Queen Mother of space telescopes, a silver fireplug floating in space with a pair of 23-foot-long solar panels that have kept it in the hunt for more than 30 years. Though it began its life in orbit inauspiciously—with an optical defect that almost ended the program, requiring a delicate NASA Space Shuttle mission to fix—Hubble has since produced staggering imagery. Among its greatest hits is the famed Hubble Deep Field—a collection of thousands of galaxies located in a relative speck of visible sky—and research that has helped narrow down the age of the universe to 13.7 billion years. (Some new calculations put the universe at 11.4 billion.) Images produced by the telescope have also helped astronomers determine that most galaxies have black holes at their centers, and allowed for unprecedented study of nearby planets, namely Jupiter and Saturn.



N°3 ‖ James Webb Space Telescope [JWST]

Manager: NASA/Space Telescope Science Institute

First light: February 3, 2022

Location: Solar orbit at Sun-Earth Lagrange point

Altitude: 160,000 to 517,000 miles

Mirror diameter: 6.5 meters

The James Webb Space Telescope, though just now entering service after its launch in December 2021, has astronomical promise, Fienberg says, and a long list of eager researchers are waiting for their time slots on the instrument. "Like Hubble, it's expected to be consistently oversubscribed by users by a large margin and able to produce lots of rewrite-the-textbooks science," he says. The new infrared telescope looks highly unconventional—its massive, dramatic gold mirror assembly sits out in the open, like it's riding on a sled—but it packs a wealth of innovation. For one, the mirrors are made with a new form of gold-plated beryllium. It's also configured in a way that allows it to remain chilled even in direct view of the sun, which is essential for infrared telescopes. Once it's fully up and running, we can expect research into possibly inhabitable exoplanets and the birth of the first stars and galaxies of the universe.

N°4 ‖ Daniel K. Inouye Solar Telescope [DKIST]

Manager: Association of Universities for Research in Astronomy

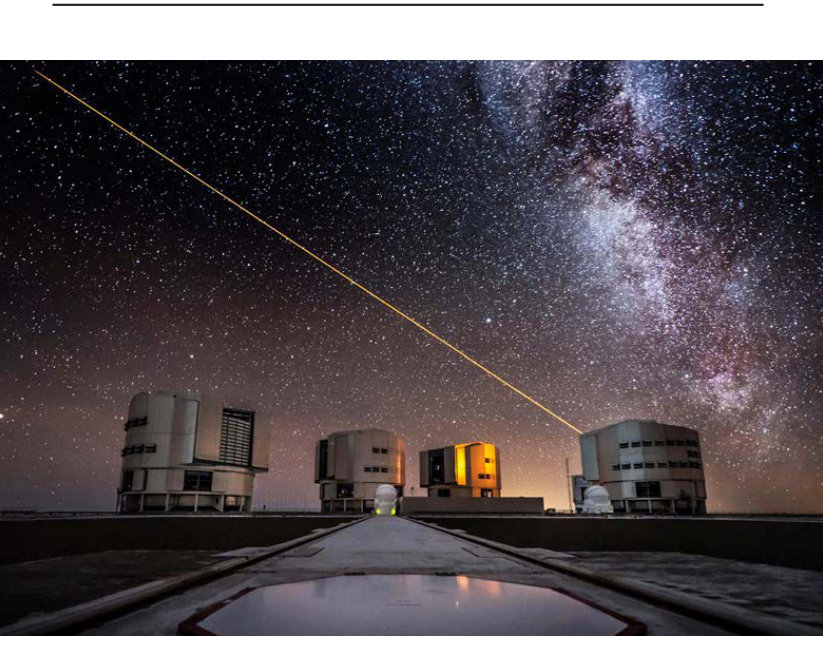
First light: December 2019

Location: Haleakalā, Hawaii

Altitude: 10,000 feet

Mirror diameter: 4.24 meters

Sitting in a massive domed housing atop Maui's Haleakalā volcano, this telescope, the largest solar observatory yet, uses a special mirror configuration that aims the light off the central axis to the camera sensor. This eliminates the need for the central obstruction that most reflectors have, and also helps the DKIST generate a cleaner, higher-resolution image of the star nearest to us—our sun. It will allow for detailed study of the star's surface and its close atmosphere, as well as analysis of the impact of magnetic fields on solar structure.



N°5 ‖ Very Large Telescope [VLT]

Manager: European Southern Observatory

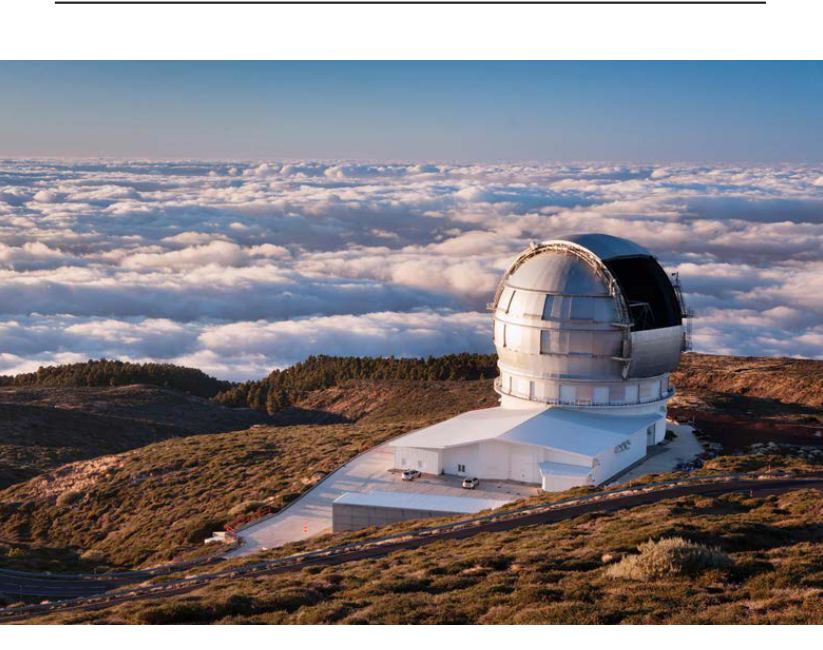
First light: 1998

Location: Antofagasta Region, Chile

Altitude: 8,645 feet

Mirror diameter: 8.2 meters each

This array of four identical telescopes situated high in the ultradry atmosphere of the Atacama Desert generates some of the sharpest images possible. That resolution comes courtesy of the array's ability to link all four telescopes together and use them as a single observing device with an aperture equivalent to the total length of the telescopes, a process called interferometry. This generates an angular resolution of 0.002 arcseconds—a measurement of how small an area of the sky it can resolve—whereas individually each scope can achieve 0.05 arcseconds. The VLT is responsible for the first image of an extrasolar planet and for capturing the farthest known gamma-ray burst. Those rays, adjacent to X-rays on the electromagnetic spectrum, signify highly radioactive sources in the universe, thus revealing a great deal about energy sources in the universe.



N°6 ‖ Gran Telescopio Canarias [GTC]

Manager: Instituto de Astrofísica de Canarias

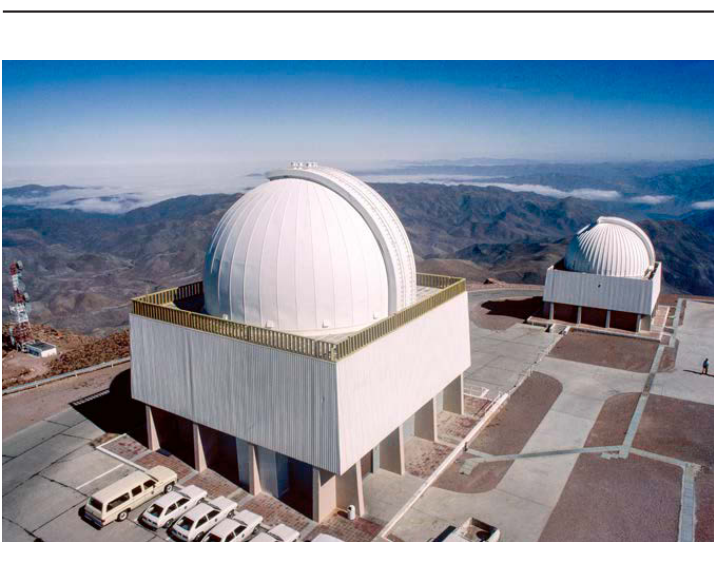
First light: July 13, 2007

Location: La Palma, Canary Islands, Spain

Altitude: 7,438 feet

Mirror diameter: 10.4 meters

The largest-aperture telescope mirror in the world is the GTC, situated high on a Canary Island mountain. Its 10.4-meter mirror uses 36 hexagonal segments, each of which can be independently moved for optimal positioning in light of its angle and the atmospheric conditions, among other factors. With it, astronomers recently discovered the farthest known black hole from Earth, found in a galaxy emitting rare gamma rays by using light emitted when the universe was less than 2 billion years old. The GTC has also produced images of the most distant galaxy ever photographed, at 500 million light years away.



N°7 ‖ Cerro Tololo Inter-American Observatory Blanco Telescope

Manager: NOIRLab

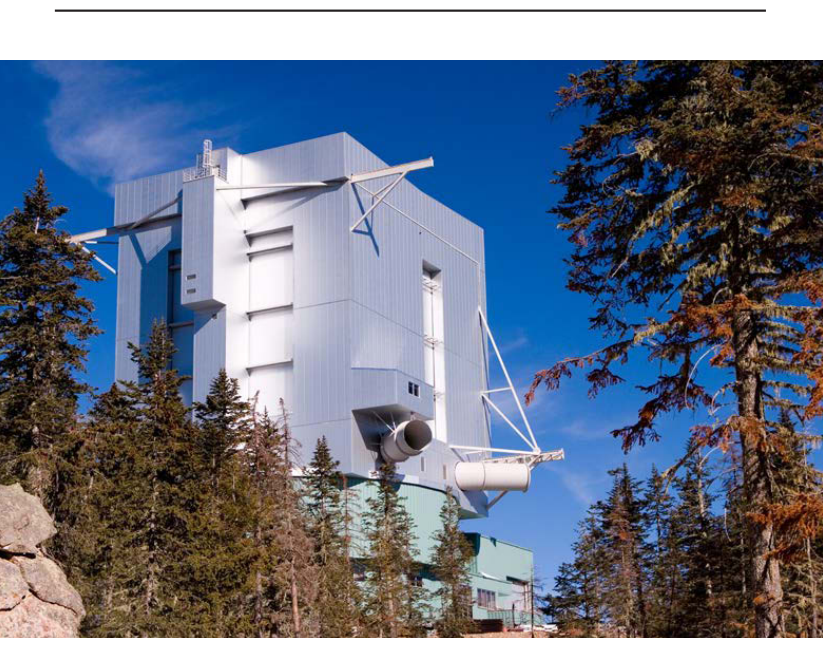
First light: 1976

Location: Coquimbo Region, Chile

Altitude: 7,241 feet

Mirror diameter: 4 meters

Located in the desert of northern Chile—a region favored by astronomers because of its minimal light pollution and dry atmosphere—this observatory conducts research on behalf of a variety of organizations and universities. Though it includes a slew of smaller telescopes that scan the heavens from the summit of Cerro Tololo, the king of the hill is the Victor M. Blanco Telescope, a 4-meter-aperture instrument that's engaged in the Dark Energy Survey. The mission of this effort is to understand the nature of the mysterious "dark energy" in the universe, which impacts the rate and nature of galactic movement through space. It uses a large special-purpose-built camera to scan for patterns in cosmic structure by mapping hundreds of millions of galaxies.



N°8 ‖ Large Binocular Telescope [LBT]

Manager: Large Binocular Telescope Corporation

First light: October 12, 2005

Location: Mount Graham, Arizona

Altitude: 10,568 feet

Mirror diameter: Dual 8.4-meter mirrors

The rare configuration of this telescope lends it a unique look among multi-mirror observatories: two identical mirrors affixed to the same mount, moving in unison, rather than on separate mounts able to move independently. The result is a telescope with the same light-gathering ability as a single 11.8-meter mirror, and with the resolution of a 22.8-meter mirror—a record for telescopes of this size and type. (The former is a measurement of mirror surface area, and the latter of the diameter of the entire system, described as its baseline.) The LBT uses an adaptive optics system, installed in 2010, that under certain conditions can generate images sharper than those of the Hubble Space Telescope.

N°9 ‖ Chandra X-Ray Observatory [CXO]

Manager: NASA and the Smithsonian Astrophysical Observatory

First light: August 1999

Location: Geocentric orbit

Altitude: 8,890 to 83,591 miles

Mirror diameter: 1.2 meters

Capturing X-ray emissions from hotter parts of the universe—an undertaking that can tell us a great deal about the composition of objects in space—is tricky. Because X-rays are absorbed by Earth's atmosphere, dedicated observatories must be lofted into space. Hence Chandra's 23-year development and eventual 1999 launch aboard the Space Shuttle *Columbia*. Fienberg notes even more unique challenges of an X-ray telescope: "The technology is very different from what's in optical, infrared, and ultraviolet telescopes," he says. "The mirrors are nearly cylindrical rather than disklike. X-rays penetrate most materials, but they can be focused if they hit a mirror at a glancing angle. Hence, X-ray telescopes consist of multiple nested not-quite-cylinders that bend the X-rays just enough to get them to focus far downstream of the mirrors." Since its launch, the telescope's nested mirrors have revealed the exploded remains of dead stars and found black holes around the universe. Last year, it located what could be the first exoplanet outside our own galaxy, in the galaxy M51, a.k.a. the Whirlpool Galaxy. (It will require additional research to be verified.)

N°10 ‖ Atacama Large Millimeter Array [ALMA]

Manager: Joint ALMA Observatory

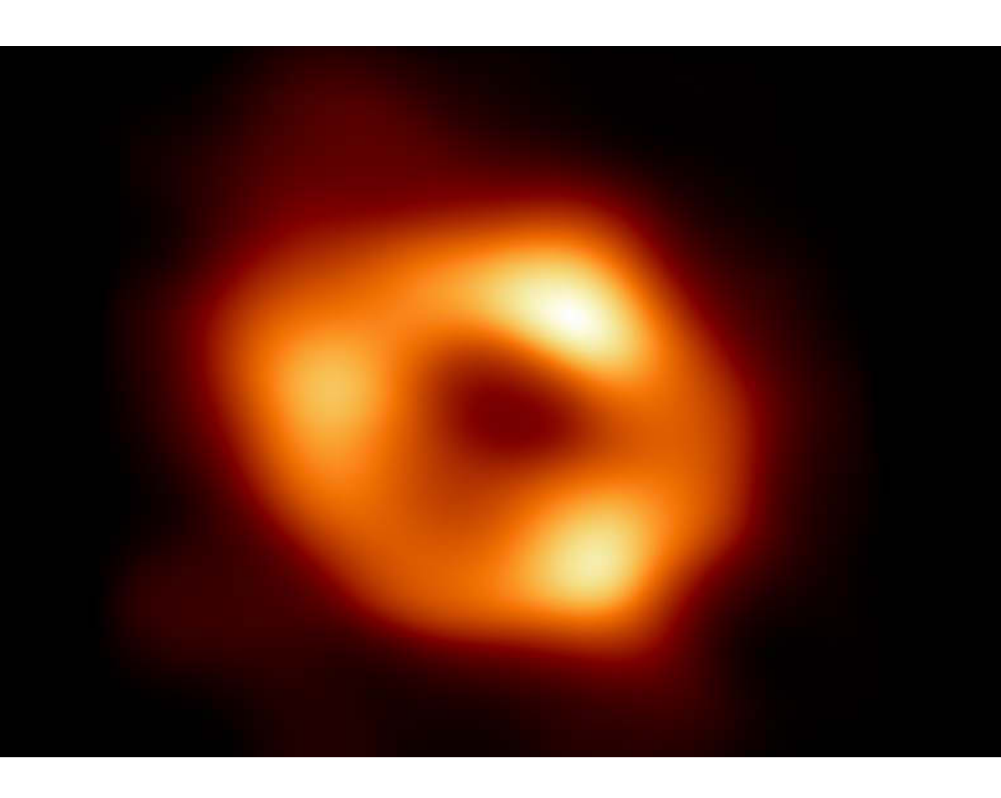
First light: 2011

Location: Antofagasta Region, Chile

Altitude: 16,597 feet

Array diameter: Up to 10 miles

The $1.4 billion multinational ALMA—operated by North American, European, and Asian partners—is the world's largest and highest-resolution radio telescope. It comprises 66 separate radio antennas—enormous curved dishes that look like overgrown satellite television receivers—sprinkled on a high-desert plateau in Chile. The dishes can be configured at a variety of distances and relative positions, with a maximum diameter of the entire array of 10 miles. Since entering service in 2011, ALMA has investigated comet matter, extrasolar planet formation, and the composition of the atmosphere of Venus, among other targets.



N°11 ‖ Event Horizon Telescope [EHT]

Manager: Event Horizon Telescope

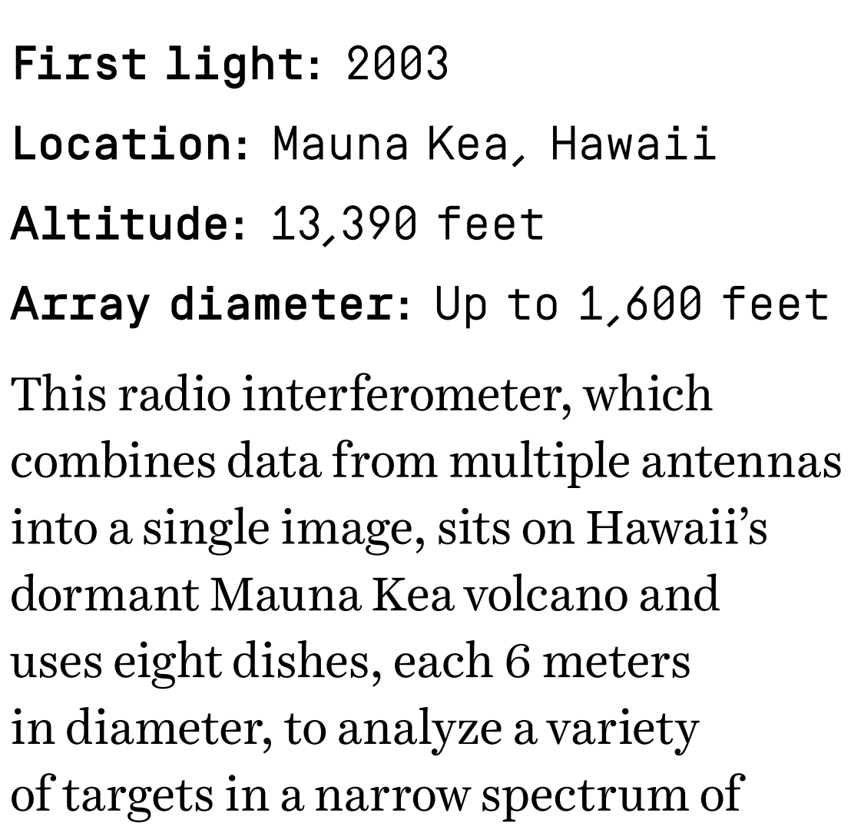
First light: 2006

Location: Earth

Altitude: Multiple

Array diameter: Earth

One of the most mind-bending innovations in astronomy is that of the "virtual telescope," which combines observations from multiple facilities and locations into a single image, with the differences generated by their relative distances from one another helping to increase the resolution. Thus we have the Event Horizon Telescope, which integrates radio telescopes worldwide in places such as Europe, South America, and Antarctica. Data from coordinated observations is combined, processed, and analyzed to generate composite images for study. In 2019 the array generated the first image of a black hole, in the galaxy M87, and in May of this year it recorded the first photographs of the black hole in the center of the Milky Way.



N°12 ‖ Submillimeter Array

Managers: Smithsonian Astrophysical Observatory and Academia Sinica

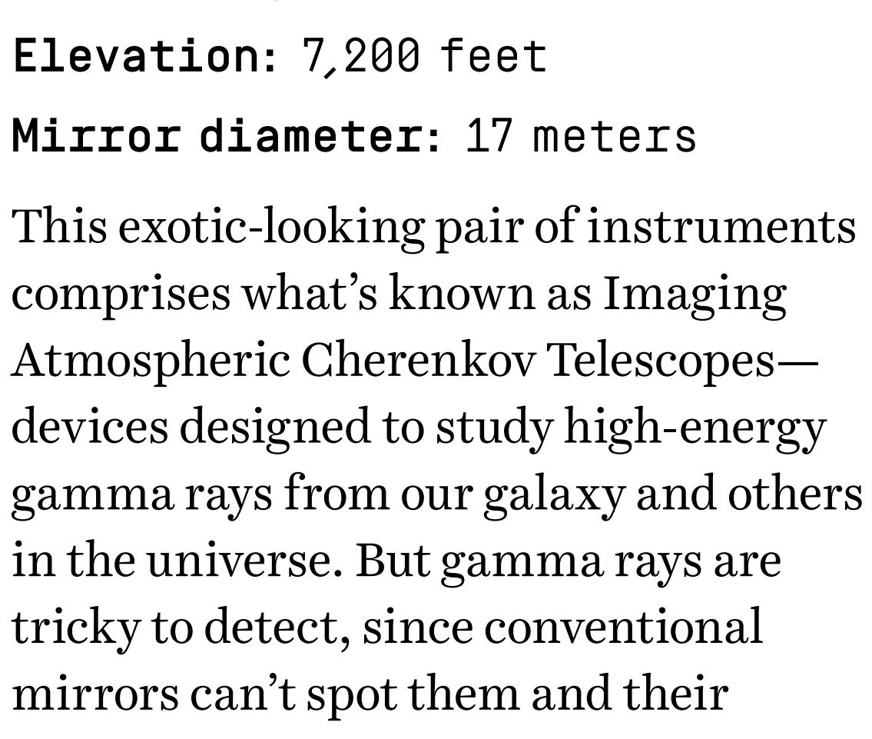
First light: 2003

Location: Mauna Kea, Hawaii

Altitude: 13,390 feet

Array diameter: Up to 1,600 feet

This radio interferometer, which combines data from multiple antennas into a single image, sits on Hawaii's dormant Mauna Kea volcano and uses eight dishes, each 6 meters in diameter, to analyze a variety of targets in a narrow spectrum of electromagnetic wavelengths. It focuses on star formation and star death, black holes and other structures at galactic centers, and the thermal and spectral emissions of a wide range of objects in our solar system. To reposition each of the 6-meter-diameter dishes for optimal use in different studies, the dishes are loaded onto custom-made transporters that look as much like mining equipment as tools of science. The transporters maintain power to the radio receivers' onboard cooling systems during their relocation, allowing the sensitive receivers to stay at the correct temperatures for observation.



N°13 ‖ MAGIC Telescopes

Manager: MAGIC Group

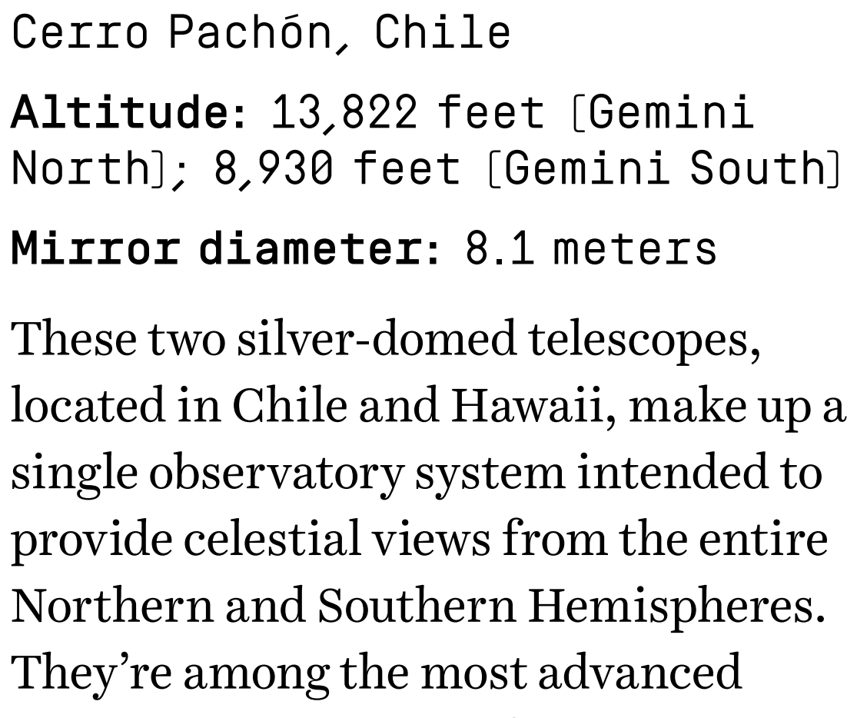
First light: 2004

Location: La Palma, Canary Islands, Spain

Elevation: 7,200 feet

Mirror diameter: 17 meters

This exotic-looking pair of instruments comprises what's known as Imaging Atmospheric Cherenkov Telescopes—devices designed to study high-energy gamma rays from our galaxy and others in the universe. But gamma rays are tricky to detect, since conventional mirrors can't spot them and their wavelengths are small enough to pass through most detectors. The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) uses 17-meter-diameter segmented mirrors engineered to detect the rays by searching for flashes of light given off as they enter our atmosphere, supported with a sleek carbon-fiber structure. The instruments study supernovas, galactic centers, and dark matter, and are run by a group of 24 astronomical organizations around the world.



N°14 ‖ Gemini Observatory

Manager: Gemini Board

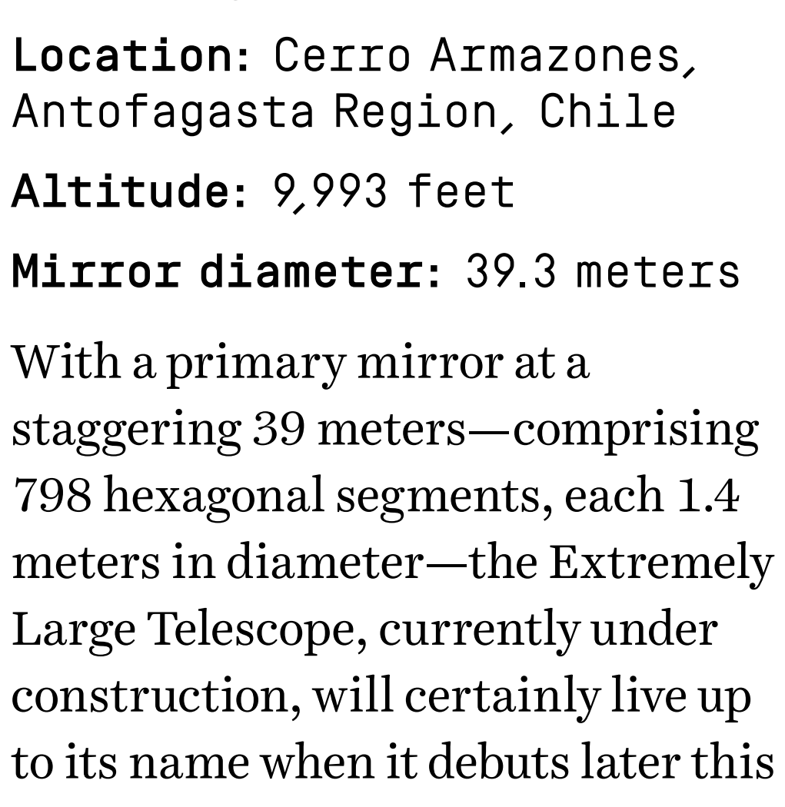
First Light: 1999 [Gemini North]; 2000 [Gemini South]

Location: Mauna Kea, Hawaii; Cerro Pachón, Chile

Altitude: 13,822 feet [Gemini North]; 8,930 feet [Gemini South]

Mirror diameter: 8.1 meters

These two silver-domed telescopes, located in Chile and Hawaii, make up a single observatory system intended to provide celestial views from the entire Northern and Southern Hemispheres. They're among the most advanced telescopes yet created, folding in laser beams aimed near the target—known as laser guide stars—that help assess atmospheric turbulence and correct the image via fast-responding adaptive optics. A silver coating on the mirrors allows for vastly improved infrared observations. Fienberg notes another key distinction: "Some telescopes are available to the entire astronomical community, whereas others are available only to the institutions involved in their construction, operation, and maintenance," he says. "The twin Gemini telescopes in Hawaii and Chile are examples of the former, available to all astronomers in all the countries that join the Gemini International Observatory partnership."



N°15 ‖ Extremely Large Telescope [ELT]

Manager: European Southern Observatory

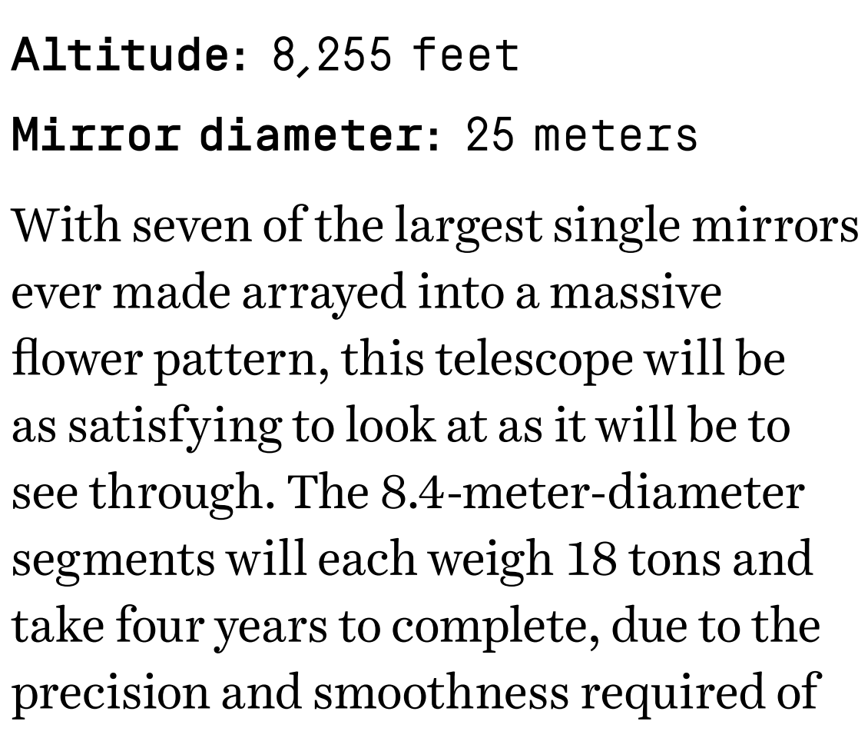
First light: 2027 [expected]

Location: Cerro Armazones, Antofagasta Region, Chile

Altitude: 9,993 feet

Mirror diameter: 39.3 meters

With a primary mirror at a staggering 39 meters—comprising 798 hexagonal segments, each 1.4 meters in diameter—the Extremely Large Telescope, currently under construction, will certainly live up to its name when it debuts later this decade. It will be four times larger than the largest current optical telescopes, allowing it to observe Earthlike planets elsewhere in our galaxy and study their atmospheres. It's also expected to be the first telescope capable of detecting evidence of life on other planets, using spectrographic analysis that will assess the composition of their atmospheres. Its massive dome will measure 262 feet high and 290 feet in diameter, while the entire telescope and support structure will weigh 3,700 tons.



N°16 ‖ Giant Magellan Telescope

Manager: GMTO Corporation

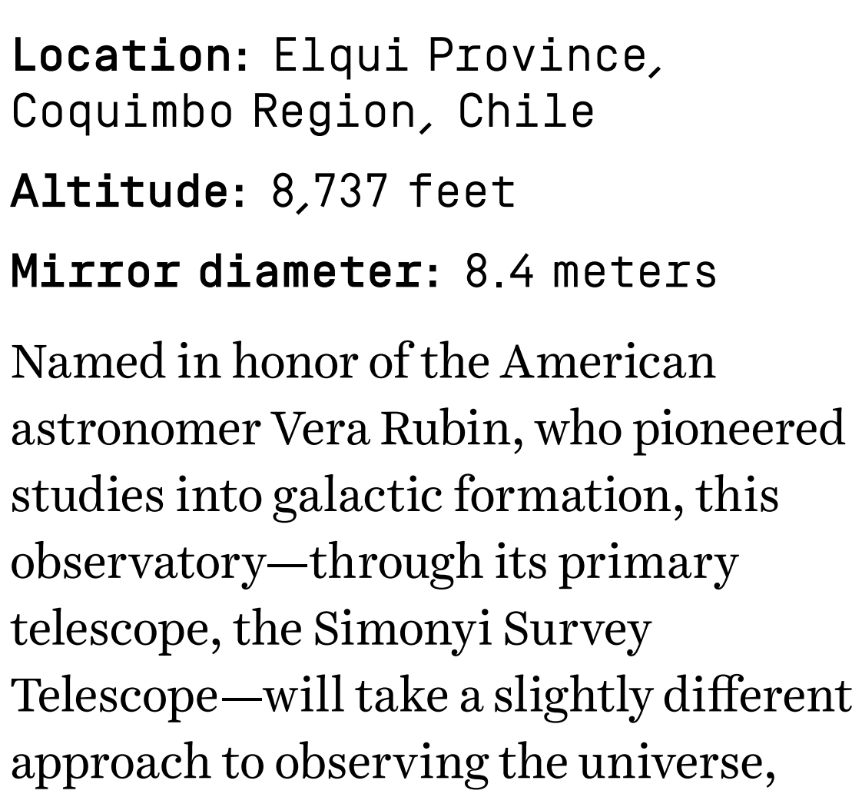
First light: 2029 [expected]

Location: Atacama Region, Chile

Altitude: 8,255 feet

Mirror diameter: 25 meters

With seven of the largest single mirrors ever made arrayed into a massive flower pattern, this telescope will be as satisfying to look at as it will be to see through. The 8.4-meter-diameter segments will each weigh 18 tons and take four years to complete, due to the precision and smoothness required of each. When ready, this instrument will have a record 10 different instruments available for studying the composition of distant planets and the early formation of galaxies.



N°17 ‖ Vera C. Rubin Observatory

Manager: Large Synoptic Survey Telescope Corporation

First light: 2022/2023 [expected]

Location: Elqui Province, Coquimbo Region, Chile

Altitude: 8,737 feet

Mirror diameter: 8.4 meters

Named in honor of the American astronomer Vera Rubin, who pioneered studies into galactic formation, this observatory—through its primary telescope, the Simonyi Survey Telescope—will take a slightly different approach to observing the universe, taking in wide-field observations instead of zeroing in on specific targets. It will make scans of the entire sky every few days using its 3.2-gigapixel camera, the largest digital camera ever built, taking 15-second exposures every 20 seconds, with a five-second period for adjusting the instrument's aim. The result will be a continuously updated survey of the sky, allowing astronomers to study movement and changes of celestial targets as well as brief changes such as supernovas and relatively fast-moving asteroids.

PHOTO CREDITS: CREATIVE COMMONS (VIDEO OF RUBIN OBSERVATORY); ALAMY (KECK, HUBBLE, WEBB, INOUYE, VERY LARGE, CANARIAS, LARGE BINOCULAR, CHANDRA, ATACAMA, EVENT HORIZON, SUBMILLIMETER, GEMINI, EXTREMELY LARGE, GIANT MAGELLAN), GETTY IMAGES (CERRO TOLOLO, MAGIC), RUBIN OBSERVATORY/NSF/AURA.

Inside Project Mayhem: America’s Top Secret Plan to Develop a Hypersonic Bomber

After Russia launched a nearly unstoppable hypersonic missile, the United States is hitting back with a bomber that can travel at Mach 10.

BY ALEX HOLLINGS

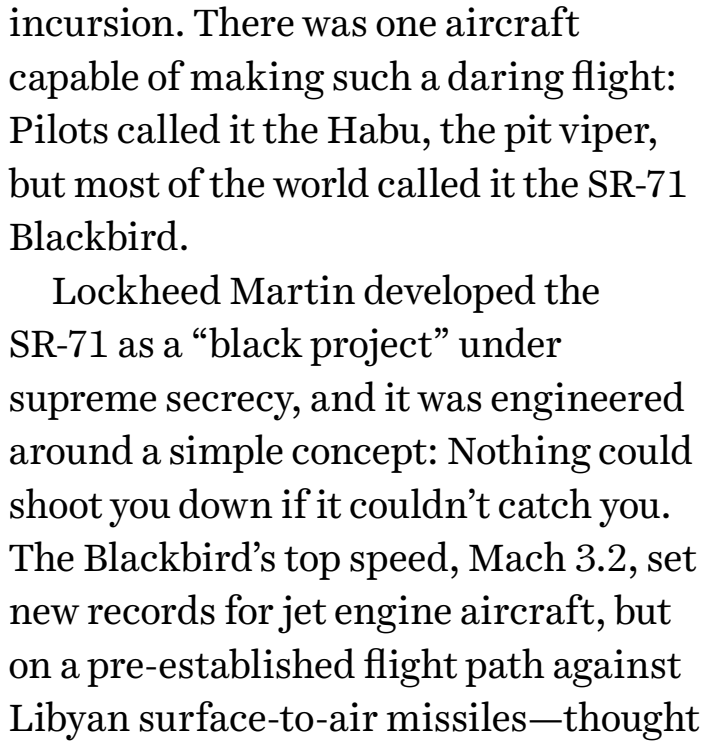
ON APRIL 14, 1986, THE U.S. Air Force lost an F-111 supersonic jet in Libyan airspace. The aircraft had participated in a retaliatory airstrike against Libyan terrorists who had attacked American servicemembers, and while the Air Force called the airstrike a success, they hadn’t expected to lose the F-111 or its crew of two. Muammar al-Qaddafi, Libya’s despotic leader, had established a “line of death” across the Gulf of Sidra, a hornet’s nest of air defense systems that would aim to shoot down anything that dared to cross it. Now the threat had substance, and the Americans had to cross the line again.

The following day, April 15, the Air Force assigned another jet to fly into Libyan airspace and assess the damage for U.S. intelligence officers. Because so little time had elapsed between this mission and the previous one, the line of death would be primed for another incursion. There was one aircraft capable of making such a daring flight: Pilots called it the Habu, the pit viper, but most of the world called it the SR-71 Blackbird.

Lockheed Martin developed the SR-71 as a “black project” under supreme secrecy, and it was engineered around a simple concept: Nothing could shoot you down if it couldn’t catch you. The Blackbird’s top speed, Mach 3.2, set new records for jet engine aircraft, but on a pre-established flight path against Libyan surface-to-air missiles—thought to be Soviet-designed SA-2s and SA-4s capable of Mach 5 speeds—it would need to push past its limits.

According to Major Brian Shul, the pilot of the SR-71, Libyan missiles shot into the sky as soon as the Blackbird crossed the line of death. The jet was already screaming at its apparent maximum speed, Mach 3.2, but Shul pushed the SR-71 even harder, trying to beat the missiles to the turn in the flight path that would take the plane out of Libya and into safety. As the Blackbird accelerated, it tore past its safety limits, its two J-58 jet engines swallowing 100,000 cubic feet of air per second. Shul’s ground speed indicator ticked past Mach 3.31, faster than 2,500 miles per hour.

More missile indicators lit up the cockpit. The SR-71 climbed above 70,000 feet, fleeing the rockets that might catch it from below. As it swung away from Libya, the plane’s speed indicator read Mach 3.5, faster than a bullet fired by an M-16. A sonic boom bellowed to the ground as the plane reached safety, an audible calling card of what remains the fastest jet-powered aircraft known to fly for any nation.



Top-secret for years, the SR-71 remains the fastest air-breathing piloted aircraft ever built. The plane entered service in 1966, with just 32 built in total. The Air Force retired it in 1998 as it focused on stealth planes. But with hypersonic missiles developed by China and Russia, speed is taking on renewed importance, and a Mach 10 replacement for the SR-71 is likely near.

The story of the SR-71’s improbable escape over Libya affirmed speed as a critical defensive tool. According to some particularly laudatory legends, the aircraft saw threats from more than 4,000 missiles during its three decades of service, and not a single one made contact. Today, stealth is the leading strategy for bypassing enemy air defenses, but as hypersonic missiles enter service in Russia and China, speed is seeing a resurgence in importance for the first time in almost four decades. And while America’s hypersonic missile programs are lagging, the legacy of the SR-71 seems to have inspired a secret plan for the Air Force to win the hypersonic arms race in another fashion. The American savior might not be a missile, but an aircraft: the near-mythical Lockheed Martin SR-72 bomber. Little is known about the top-secret program developing the technology needed to bring the hypersonic plane to life, but we do know that it has a name: Project Mayhem. Through interviews with experts and analysts, poring over government documents and looking for clues in the scant public statements and images, we’ve pieced together the most complete picture of what America’s next hypersonic weapon may look like, and how well it stacks up against the best tech from Russia and China.

THE RACE FOR SPEED supremacy took on heightened urgency in March 2018, when Russian President Vladimir Putin announced that he possessed the world’s first operational hypersonic missile, the Kh-47M2 Kinzhal. Hypersonic weapons are certainly fast—the term “hypersonic” describes flight speeds in excess of Mach 5—but it’s these weapons’ unique coupling of speed with maneuverability that confounds modern air defenses. Even state-of-the-art defense systems can’t accurately intercept platforms moving at hypersonic speeds while changing course. As a result, Russia, China, and the United States are competing to field different types of hypersonic missiles. Russia and China claim to have some in service; the U.S. is apparently falling behind.

One possible reason for that lag, analysts say, is that America’s plans for hypersonic technology are more ambitious than simply propelling a warhead beyond Mach 5. One goal is to develop a reusable hypersonic aircraft that could thwart enemy air defenses while also averting the prohibitive cost of single-use hypersonic weapons. The U.S. has pursued this capability for decades; by this measure, it once led the world in hypersonic technology. In 1957, Boeing proposed the X-20 Dyna-Soar spaceplane for bombing and reconnaissance (Neil Armstrong was among the pilots chosen for the program), and in 1967, Air Force test pilot William “Pete” Knight flew his rocket-powered North American X-15A-2 at a speed of Mach 6.7. By 2004, NASA’s scramjet-powered X-43A reached Mach 9.6, and in 2007, reports surfaced about Skunk Works and the Air Force working on a pilotless dual-mode scramjet-powered follow-up to the SR-71, dubbed the SR-72.

Russian MiG-31 supersonic interceptor jets can carry hypersonic Kinzhal missiles, which can outrun and outmaneuver all known air defenses. The Kinzhal’s appearance in the war in Ukraine brought fresh emphasis to hypersonic technology, though the utilization of this tech by the U.S. might differ heavily from that of Russia and China.

By 2015, the SR-72 was no longer hidden behind a “black project” veil—its page on Lockheed Martin’s website advertised that it could be in service by 2030. Up until March of 2018, Lockheed was public about its efforts to field the SR-72, but immediately after Putin’s speech announcing the Kinzhal, the company redacted any outward-facing mention of the plane, either because it gave up on the effort or because it was pushed back into the shadowy world of projects using classified funding.

Meanwhile, the hypersonic weapons fielded by America’s competitors thus far are similar to ballistic missiles, albeit much faster. Known as boost-glide vehicles, they’re propelled to hypersonic speeds by a rocket before detaching and gliding back toward their target at speeds as high as Mach 20. How boost-glide weapons shift course remains a secret, but experts like Chris Combs of the University of Texas at San Antonio, who specializes in hypersonics and aerospace engineering, suggest that it’s likely done using a combination of gas-powered thrusters and hydraulic control surfaces.

The other type of hypersonic weapon, which has yet to reach service for any nation, is the hypersonic cruise missile, powered by a supersonic-combustion ramjet engine, or scramjet—the same experimental propulsion technology believed to be tapped for the SR-72. A hypersonic cruise missile flies similarly to an aircraft or suicide drone, but it doesn’t work well at low speeds because its engine’s compression system relies on fast-moving air entering the engine. “Air-breathing, scramjet systems typically require a rocket booster to get started,” Combs says.

And currently, all hypersonic weapons share a common downside: cost. A recent Pentagon assessment revealed that America’s current crop of hypersonic missiles in development might cost between $89.6 million and $106 million each. That’s more than an F-35A fighter jet—expensive to the point of being prohibitive. However, in August 2020, the Air Force created a new program to its growing field of hypersonic efforts (70 projects in total, as of 2021). This one, known as Mayhem, aims to field a “multi-mission cruiser” powered by an “air-breathing hypersonic” propulsion system—a technical way of describing a ramjet or scramjet. In terms of cost alone, a hypersonic multi-mission cruiser could be a significant game changer. In terms of capability, it could shift the world’s balance of hypersonic power back to America.

ACCORDING TO AN AIR Force contract notice released in December 2021, Mayhem aims to field a “hypersonic multi-mission ISR [intelligence, surveillance, and reconnaissance] and strike” platform that can carry at least three kinds of payloads. Two of them are types of weapons, listed in Air Force documents as an “area effect” and a “large unitary payload,” while the third would be dedicated to the SR-71’s old specialty, reconnaissance. Based on those documents, it’s likely that the weapon being developed under Project Mayhem is not a hypersonic missile, but a hypersonic drone with the same operational parameters as the rumored SR-72.

Further, it appears that the military is developing a new type of engine to propel the SR-72. As NASA has learned through years of experimental testing, a traditional scramjet engine wouldn’t meet the needs of Project Mayhem’s multi-mission purpose, as scramjets function only at high speeds. Instead, Lockheed Martin appears to be developing a combined-cycle scramjet that incorporates a traditional jet engine into its design. An engine of that type would be a massive leap forward from what’s available now, and require sophisticated engineering to solve the many design challenges. It’s likely what’s holding the project back.

Conventional jet engines use a centrifugal compressor, or spinning fan blades, to compress the air flowing in before mixing it with fuel and detonating it for propulsion. Scramjets forgo a compressor in favor of using the immense pressure of high-speed airflow into the engine. As a result, scramjets sustain higher velocities than jet engines, but at lower speeds the inflowing pressure of air isn’t enough for the scramjet to function well. That means a scramjet-powered platform can’t fly slow enough to land, and as such, can be used only once. But a combined-cycle scramjet that incorporates a traditional jet engine could fly just like an aircraft, and feasibly see repeated use. “This type of engine could revolutionize air travel and defense,” Combs says.

> » MULTI-CYCLE SCRAMJET PROPULSION WOULD MAKE AN AIRCRAFT AS IMPOSSIBLE TO STOP AS A HYPERSONIC MISSILE.

Rather than destroying an expensive scramjet by using it to power a single-use missile, Mayhem may use a combined-cycle scramjet to power a drone. This system would use the traditional jet engine to take off and accelerate to around Mach 3 before transitioning to a scramjet that would launch it beyond Mach 5. Once in enemy airspace, Mayhem could deploy inexpensive conventional bombs and missiles at targets, or conduct reconnaissance, before flying home to rearm and do it all again, just like Brian Shul’s SR-71 over Libya.

It’s enticing in theory, but confounding and even paradoxical from an engineering standpoint. The compression system of a turbine impedes airflow by design, but a scramjet needs unobstructed airflow to operate. A successful engine would have to merge two seemingly contradictory designs. “It’s hard to build hypersonic cruise aircraft that can take off from a runway,” says Skyler Shuford, chief operating officer of Hermeus, a start-up developing a reusable ramjet-powered aircraft known as Quarterhorse. (In ramjet engines, combustion takes place at subsonic speeds.) “What’s optimal for takeoff is very different from what’s optimal to break the sound barrier, and both are very different from what’s optimal at hypersonic speeds. Many of these [factors] are extremely sensitive and hard to predict on the ground.”

The challenges inherent to developing even normal scramjets are immense, particularly when it comes to igniting an air-fuel mixture as it passes through an engine at faster than the speed of sound. (Combs calls this challenge “flame holding.”) To date, no nation has managed to field a scramjet propulsion system in a missile, let alone an aircraft, though the U.S. has run some encouraging tests. During the fall of 2021, Northrop Grumman conducted a successful flight of a missile-sized scramjet as a part of DARPA’s Hypersonic Air-breathing Weapon Concept (HAWC) program, and in March 2022, Lockheed Martin followed suit as a part of the same effort.

The technology powering Mayhem is an extension of scramjet systems currently found in HAWC, but the scramjets used for HAWC offer only half of the combined-cycle recipe needed for a platform like Mayhem, or the SR-72. In order for Mayhem to fly like an aircraft, the Air Force still needs to develop a way to incorporate a traditional jet engine into the mix without blocking airflow into the scramjet or making the aircraft too heavy to fly.

THE HYPERSONIC ARMS race runs parallel to stealth aircraft technology, but it nonetheless affects how militaries develop and utilize that tech. America is the obvious global leader in this area. It boasts two stealth fighters in service, the F-22 and F-35, and the world’s only operational stealth bomber, the B-2 Spirit. The U.S. has two next-generation stealth fighters in development, plus a successor to the B-2. But other nations are beginning to field effective counter-systems.

Stealth technology is limited by physics when utilized on a fighter jet. In order to offer the aerobatics necessary for the fighter class, these jets need vertical tails, moving control surfaces like flaps and ailerons, and open mouths to feed the jet turbines inside the fuselage. These elements are prone to producing easily readable radar returns. Stealth jets aren’t actually invisible to radar; they just reflect minimal energy. In fact, many can be easily spotted using lower-frequency radar bands.

Savvy detection systems partner these low-frequency arrays with other instruments and surface-to-air missiles (in 1999, this combination shot down a stealth F-117 Nighthawk with a Soviet-era SA-2) or multistatic radar arrays that can read returns from multiple areas, not just from where the signal was broadcast. The added sophistication has troubled the Air Force; its experts have assessed that beyond 2030, even the F-22 will no longer be survivable in contested airspace.

This rendering, released in 2016 by Lockheed Martin, shows the company’s vision of the SR-72. Speculation about the aircraft’s capabilities abound: Some claims project that a prototype could fly by 2025, and that the plane could fire hypersonic missiles. The SR-72’s relationship to Project Mayhem is unclear.

That leaves an opening, and an urgent need, for Project Mayhem’s speed-first approach. Multi-cycle scramjet propulsion would make an aircraft as impossible to stop as a hypersonic missile. The drone aircraft produced by Mayhem could fly into enemy territory, engage a target or gather intelligence, and fly out again without being shot down. And as Air Force Secretary Frank Kendall has explained about other drone programs in development, not having a pilot onboard can allow the aircraft to take greater risks.

That would represent a significant cost saving over $100 million hypersonic missiles. Most of America’s arsenal of air-launched missiles and bombs range in cost from tens of thousands up to a few million dollars each. Rather than these weapons being seen as outdated, they could remain just as effective if delivered to targets at hypersonic speeds from inside the bomb bay of an aircraft. A combined-cycle scramjet aircraft such as Lockheed Martin’s SR-72 could allow the U.S. to leapfrog the high-Mach capabilities being fielded by Russia and China, and it could carry many of America’s existing munitions with it into the hypersonic age.

Alas, putting different payloads on a hypersonic plane requires more finesse than simply lashing them to a wing the way one might tie down camping gear atop a minivan. “Going Mach 5 and faster generates extreme levels of heat, driving the need for innovative materials, sensors, and electronics to withstand such speeds throughout its journey," says Dave Berganini, vice president of hypersonic and strike systems at Lockheed Martin Missiles and Fire Control. "These systems must be able to maintain consistent communication connections to perform precise maneuverability techniques and overcome a range of defense systems and extreme environments." In other words, you need to keep the bags on top of the minivan while driving at 3,800 miles per hour, steering around potholes, and dodging oncoming traffic at the same time.

WHILE OFFICIAL information is scant, some clues are emerging that the U.S. Air Force and its Mayhem partners may be further along than many initially thought—or even believed possible. In January 2018, about a month before Putin kicked off the hypersonic missile race, Jack O'Banion, Lockheed Martin's vice president of strategy and customer requirements for advanced development programs, discussed the SR-72 on the record at a conference as if it already existed. He seemed to suggest the aircraft's scramjet propulsion systems had already been tested, and when an artist's rendering of the SR-72 appeared on the screen behind him, O'Banion told the crowd that the aircraft could only have been built thanks to the "digital transformation."

"[The engine] would have melted down into slag if we had tried to produce it five years ago," O'Banion said. "But now we can digitally print that engine with a sophisticated cooling system integral into the material of the engine itself, and have that engine survive for multiple firings for routine operation." Later, O'Banion told the press that the "aircraft is also agile at hypersonic speeds, with reliable engine starts."

Although Lockheed Martin removed any mention of the SR-72 from its website just a few months later, the U.S. has since tipped its hand to imply that Project Mayhem might have some intersection with the long-rumored plane, or at least a hypersonic jet in general. In December 2021, the Air Force Research Laboratory in charge of developing new warfighting technologies released an updated contracting document for Mayhem that removed key terms like "expendable" and "demonstrator" from its description. It also stated that the Mayhem vehicle will need to execute "multiple missions" with an air-breathing hypersonic system.

The relationship between the SR-72's development and the Project Mayhem aircraft is unclear: The projects could be borrowing from one another, or not related at all. It's possible that when Lockheed Martin wiped the SR-72 from its public-facing list of projects, it was giving up on the effort. It's also possible that the high-stakes context of a hypersonic-capable Russia and China have pushed the SR-72 to the secret depths of the Air Force's vault of classified programs.

Lockheed Martin won't say, but on June 2, the contractor released a statement about the fictional, combined-cycle, scramjet-powered aircraft named Darkstar that is featured in this summer's aviation blockbuster, *Top Gun: Maverick*. Not only did Lockheed Martin's Skunk Works help design and build a full-scale mock-up of the hypersonic aircraft for filming, but it also hinted in a statement that the plane's performance might go beyond movie magic: "Darkstar's capabilities could be more than mere fiction. They could be reality."

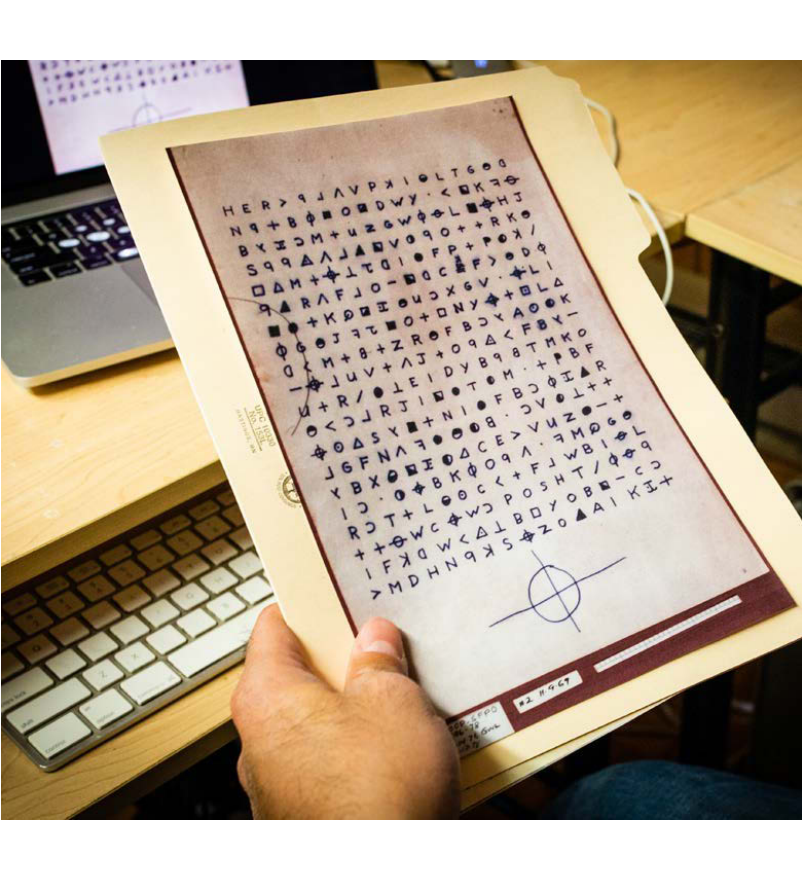
Whether Mayhem ultimately produces something like the SR-72 or another hypersonic platform, it seems clear that the program's multi-cycle scramjet technology is a matter of "when," not "if." But as America's stealth advantage narrows and its potential near-peer opponents gain technological strength, the question of "when" is becoming more important than ever.

LOCKHEED MARTIN (TOP, SR-72); GETTY IMAGES (SR-71, MIG-31)

How Three Amateurs Solved the Zodiac Killer’s ‘340’ Cipher

The mysterious code stumped the FBI and NSA for 53 years. What does the key, and the resulting solution, tell us about the murderer?

BY KATHRYN MILES



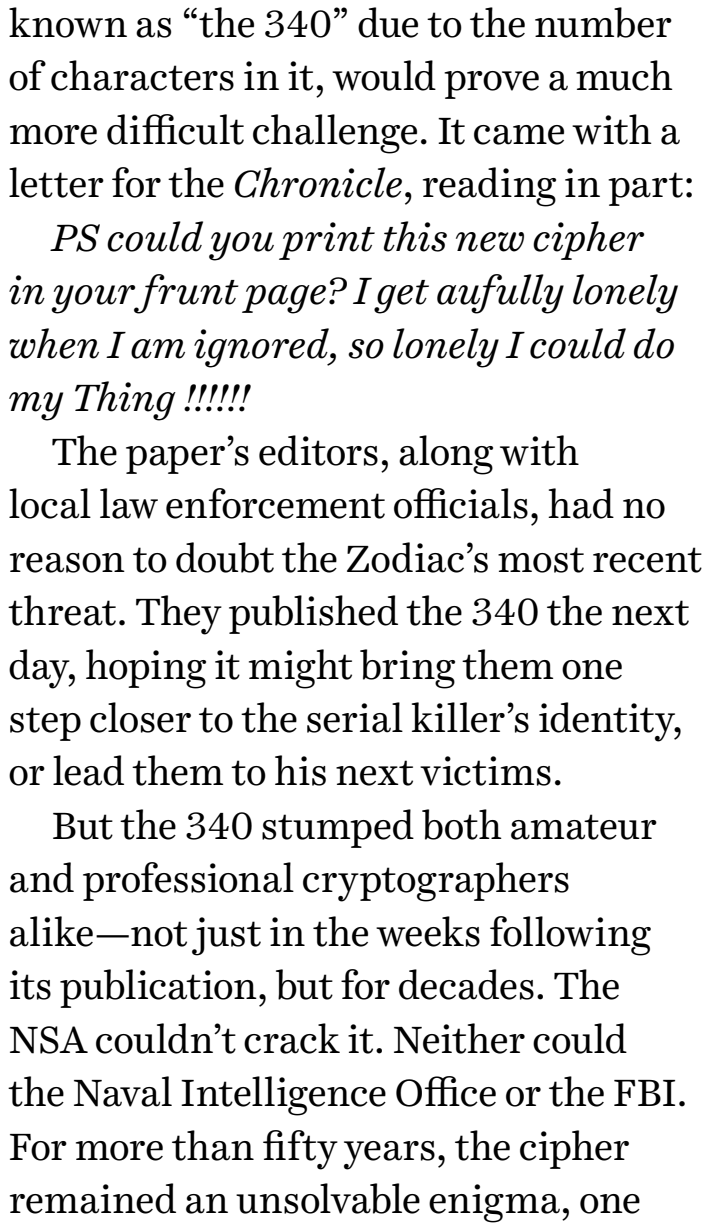
THE ENVELOPE ARRIVED at the *San Francisco Chronicle* in November 1969 without a return address, its directive to the recipient, in handwriting distinctively slanted and words unevenly spaced, to “please rush to editor.” The *Chronicle* newsroom had seen the scrawl before, on previous letters sent from the Zodiac, a self-monikered serial killer who threatened to go on a “kill rampage” if the paper didn’t publish his writing on its front page. By the time of the November letter, the Zodiac had already attacked seven people, murdering five. His most recent murder—of a San Francisco cab driver, by gunshot—had occurred just four weeks before this new envelope arrived. The Zodiac had mailed the *Chronicle* a piece of the victim’s bloodied shirt as evidence of the crime.

The Zodiac’s letters were replete with grisly imagery. He signed his “name” with a crosshairs symbol. He shared haunting details of his attacks. He promised to blow up buses of schoolchildren and unleash a “death machine” on San Francisco. But in addition to these overt threats, he included baffling ciphers for investigators to crack, troubling grids of symbols and letters that presumably masked a secret about his identity, intentions, or victims (to this day, the killer has never been found). The Zodiac’s first cipher, included in the July 31 letter, had been solved within a week by an amateur husband-and-wife team—but it had only revealed more of the killer’s raving. The second, now known as “the 340” due to the number of characters in it, would prove a much more difficult challenge. It came with a letter for the *Chronicle*, reading in part:

PS could you print this new cipher in your frunt page? I get aufully lonely when I am ignored, so lonely I could do my Thing !!!!!!

The paper’s editors, along with local law enforcement officials, had no reason to doubt the Zodiac’s most recent threat. They published the 340 the next day, hoping it might bring them one step closer to the serial killer’s identity, or lead them to his next victims.

But the 340 stumped both amateur and professional cryptographers alike—not just in the weeks following its publication, but for decades. The NSA couldn’t crack it. Neither could the Naval Intelligence Office or the FBI. For more than fifty years, the cipher remained an unsolvable enigma, one that grew to almost mythic proportions among codebreakers and cryptography sleuths. Some speculated that the cipher would never be solved—that it was too sophisticated, too challenging for even contemporary cryptographers.



The 340 cipher, above, reached the *San Francisco Chronicle* in November 1969. The killer’s first cipher had been cracked in a week by an amateur husband-and-wife team. Solving this one would require the eventual codebreakers to employ homophonic substitutions, period-19 transposition, the knights tour, and other complex cryptology schemes.

But then, in December 2020, the FBI announced a breakthrough: The 340 cipher had been solved. Not by its crack Cryptanalysis and Racketeering Records Unit, but instead by three computer wonks who’d found one another on an obscure online true-crime discussion board and started collaborating during the COVID-19 pandemic. The trio, who had no background in cryptology and no professional codebreaking experience, did what the world’s most powerful intelligence organizations could not. On top of the solution’s haunting opacity, the intricacies of the cipher itself brought fresh layers of insight that, forensic experts say, might help authorities eventually, finally, catch up to the killer.

“THERES NOT A LOT OF RHYME OR REASON TO IT, WHICH MAKES IT IMPRESSIVE THAT ANYONE SOLVED IT.”

DAVE ORANCHAK HAS always been a puzzle geek. When he’s not running ultramarathons near his home in Roanoke, Virginia, the 47-year-old computer programmer spends most of his time working out practical solutions to problems, whether in his coding work or his passion for Shinro, a Japanese derivation of Sudoku. Around 2006, Oranchak became intrigued by the 340’s apparent resistance to a solution, a key had eluded the best efforts of professionals and experts. Tempted by the chance to unlock a slate of notorious cold cases, he started nosing around online discussion boards about the Zodiac. Before he knew it, he was down the rabbit hole, immersed in the Zodiac’s story and gaining a reputation as one of the reigning experts on the killer’s ciphers.

The Zodiac had a thick case file for amateur sleuths like Oranchak to peruse. Here was a serial killer who had gone out of his way to taunt the police. His handwriting was on file, along with a recording of his voice. Witnesses to his crimes had provided enough information for law enforcement to create a composite sketch of his face. The Zodiac had tallied his victims in marker on the side of a car, drafted homemade ciphers, and mailed scraps of evidence to newspapers. But despite the best efforts of the country’s leading intelligence agencies, no one knew who he was. The 340 cipher was one of the final threads to pull, a puzzle with seemingly no discernible rules, schemes, or internal logic.

Oranchak dedicated hundreds of hours to the 340 cipher—“way too many,” by his own measure. As his commitment deepened, he became a respected moderator on the Zodiac discussion boards and the leading authority on the 340 itself. He appeared on TV documentaries and podcasts dedicated to the Zodiac, eventually giving talks at NSA-sponsored cryptology conferences and sitting on panels with FBI agents actively working in the cryptology field.

One of the three amateurs who broke the 340 code, David Oranchak did most of his work from his home office, his dog Rosa by his side while he sat at his computer. He detailed his thought processes and methods on his YouTube channel, where he connected with others attempting to crack the cipher.

The community of amateur Zodiac hunters can be sensationalistic. “There’s a lot of chatter and nonsense and arguing about suspects,” Oranchak says. But one member of the forums struck him as level-headed and critical: Jarl Van Eycke, a reclusive warehouse worker living in Belgium who had gained respect in the cryptology community after developing his own decryption software program. “Jarl was technically minded, and [he was] approaching the [Zodiac] problem rationally,” Oranchak says.

Van Eycke declined an interview request for this story. And he’s never spoken on the record about his decryption software or the Zodiac case. Oranchak has never met him; they’ve corresponded only by email and on forums. Despite Van Eycke’s almost total obscurity, he agreed to work with Oranchak on a solution to the 340. That was a pivotal moment that would add speed to the codebreaking process; Van Eycke’s software could work through multiple solution sequences simultaneously and provide a rating for the correctness of each result.

Van Eycke and Oranchak began programming the codebreaking software to work through thousands and thousands of possible solutions to the 340 cipher. During the pandemic, Oranchak launched a YouTube channel dedicated to their work from his home office; his family vacation photos and a watercolor portrait of the late family cat, Peabody, looked on as he issued heady primers about cryptology and codebreaking.

Despite the homespun setting, the information in Oranchak’s videos was undeniably sophisticated. He used Scrabble tiles to explain substitution keys and anagrams and gave casual lectures on cipher organization strategies such as columnar transposition, in which messages are first written in columns rather than lines. Before long, videos on his channel had millions of views. Oranchak was sure that certain anomalies in the cipher pointed to a logical organizational strategy. While some dismissed the cipher as an impossible exercise from a deranged mind, Oranchak believed that a valuable solution lay behind the inscrutable symbols.

ORANCHAK’S BELIEF IN THE 340’s logic stemmed from cryptography’s foundational principles. Ciphers date back at least 3,000 years. The earliest known cryptogram is from 1500 B.C., when a Mesopotamian potter devised a code to keep his glaze recipe secret from competitors, but methodologies have diversified and proliferated since then. Ancient Spartans and Chinese military leaders used the “scytale” method, writing messages that could only be read when wrapped around a specific rod, and Julius Caesar popularized the substitution cipher, in which each letter is replaced by another letter that’s a set number of positions away in the alphabet. Sir Francis Bacon favored a “steganographic” approach in which he replaced letters with binaries, and during each of the World Wars, countries used a range of cryptography methods, from simple stencils to the legendary German Enigma machine. All of these cipher varieties employ rotating substitutions that can be “brute forced” by nothing but pencil and paper, says Riad Wahby, Ph.D., whose research at Carnegie Mellon University focuses on proof systems and cryptography. This quality makes them accessible to the public despite their many layers of complexity.

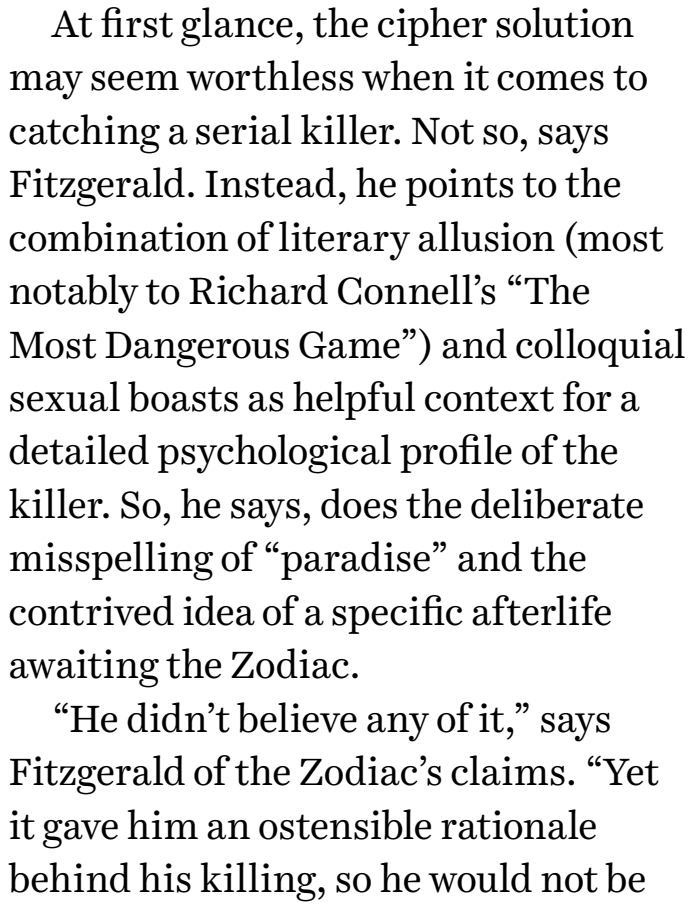
By the time the Zodiac began his killing rampage in 1968, ciphers and other cryptograms had invaded pulp crime novels and detective magazines. Readers could learn organizational tricks, such as the knight’s tour or period-19 transposition, and then use them in ciphers of their own. The Zodiac himself likely came of age reading some of those detective magazines and codebooks, says James R. Fitzgerald, a forensic linguist and criminal profiler who spent much of his career at the FBI’s Behavioral Analysis Unit. “If Zodiac is ever identified and his house is ever searched, you’re going to find dozens and dozens of other codebooks, other pads of paper with other code written on them,” he says. “He had an extended interest in this kind of language usage.”

According to Fitzgerald, the Zodiac’s schematics align with popular cryptology strategies of the time. The first cipher was simple—a substitution code containing 26 symbols, each of which stood in for a letter in the English alphabet. Donald Harden, a high school teacher, and his wife, Bettye, solved it within a week of its publication. The couple estimates that they spent about 20 hours on the puzzle. They zeroed in on easy-to-find words likely to be used by a murderer; “kill,” for example, has repeating letters. Then they followed rules known to any Wheel of Fortune fan: namely, that E is the most used letter in the English language, as are certain letter pairings, such as T-H and Q-U. The solution read, in part:

> I LIKE KILLING BECAUSE IT IS SO MUCH FUN. IT IS MORE FUN THAN KILLING WILD GAME IN THE FOREST BECAUSE MAN IS THE MOST DANGEROUS ANIMAL OF ALL. TO KILL SOMETHING GIVES ME THE MOST THRILLING EXPERIENCE. IT IS EVEN BETTER THAN GETTING YOUR ROCKS OFF WITH A GIRL. THE BEST PART OF IT IS THAT WHEN I DIE I WILL BE REBORN IN PARADICE AND ALL I HAVE KILLED WILL BECOME MY SLAVES.

At first glance, the cipher solution may seem worthless when it comes to catching a serial killer. Not so, says Fitzgerald. Instead, he points to the combination of literary allusion (most notably to Richard Connell’s “The Most Dangerous Game”) and colloquial sexual boasts as helpful context for a detailed psychological profile of the killer. So, he says, does the deliberate misspelling of “paradise” and the contrived idea of a specific afterlife awaiting the Zodiac.

“He didn’t believe any of it,” says Fitzgerald of the Zodiac’s claims. “Yet it gave him an ostensible rationale behind his killing, so he would not be seen by the public as just randomly and purposelessly choosing his victims.”



Clockwise from top left: The message accompanying the Zodiac’s 340 cipher sent to the *Chronicle*, taunting authorities about his most recent crimes and hinting at possible crimes to come; the code wheels and lampboard from a four-rotor German Enigma machine made during World War II, for which the user had to know the specific key settings used by the transmitter to decrypt a message; Donald G. Harden, a schoolteacher living in Salinas, California, broke the Zodiac’s first cipher sent on July 31, 1969, with his wife, Bettye June Harden; James R. Fitzgerald, a criminal profiler for the FBI from 1988 to 2007, is a forensic linguist whose work has been integral to the Unabomber, D.C. sniper, and JonBenét Ramsey cases.

BEHAVIORAL criminologists who have worked the Zodiac case surmise that the 340’s construction was informed by the ease with which the first cipher was solved—a real blow to the killer’s inflated ego. For the 340, the Zodiac increased the number of individual characters to 50 and organized them via a far more complicated cryptogram. The cipher relied upon homophonic substitution, which assigns multiple symbols to a single letter and helps mask common letter pairings. As the cipher’s key—cryptology speak for a solution—continued to elude investigators at the FBI and NSA, cryptanalysts began to suspect that the Zodiac had somehow rearranged the order of the symbols, too, possibly including purposeful mistakes in the cipher that would confuse straightforward solutions—“a code within a code,” says Fitzgerald. He says the Zodiac, in this respect, fancied himself a kind of criminal mastermind. “The true code writer is very rare, even rarer among serial killers or serial offenders. And the ones that are difficult to break are the rarest of the rare.”

The ready solution to the first cipher might have led the killer to overcomplicate the second, including the usage of what Fitzgerald calls “false flag mistakes” to throw off codebreakers. “He wanted to become more of an enigma that he already was,” Fitzgerald says. “He thrived on that. This guy wanted to put himself above and beyond all those pedestrian-type killers.” This egotism might have also informed the Zodiac’s moniker, symbol, and costume, which eyewitnesses said resembled that of a medieval executioner. It’s also why he seemed to thrive on sending mail to newspapers and demanding airtime from TV programs. On one such show, a man claiming to be the Zodiac phoned in to say that his only worry was eventually being taken to the gas chamber, a fear inconsistent with the killer’s supposed megalomaniacal arrogance. Sure enough, the caller was later proved to be a fraud.

The Zodiac affected a persona who not only delighted in taunting authorities, but who also became bored with killing and needed to invent games to keep himself amused. The cipher is the primary symbol of the killer’s paradoxical needs to be both obsessed about and unknowable. That twisted psychology contributed to its immense difficulty, and is one reason why it took decades to unpack.

“ZODIAC KILLED FOR THRILL. THE CIPHERS ONLY ADDED TO THE THRILL, ONCE THE KILLINGS BECAME ROUTINE.“

AS COVID LOCKDOWNS persisted in 2020, Jarl Van Eycke continued to refine his codebreaking software, AZDecrypt. He reported to Zodiac listserv users that it was becoming faster and more efficient, and he was adding features that allowed users to freeze keywords in the cipher, such as “kill,” while running permutations on the other symbols—a process called “cribbing” that can narrow the number of possible combinations a program needs to try. On his YouTube channel, Dave Oranchak theorized that the Zodiac had probably used a combination of schemes in the 340, including the knight's move, in which a message is rearranged in a manner following the moveset of a knight in chess, and period-19 transposition, in which each character is moved 19 positions in the cipher before solving.

That video caught the eye of Sam Blake, a quantitative analysis researcher at the University of Melbourne. Burned out from his work in computing infrastructure, Blake found Oranchak's channel a more relaxing way to problem solve. He joined the Zodiac hunt with traditional pen and paper at first, but found it "clunky" for interacting with the more complex schemes AZDecrypt was dealing with. Period-19 transposition in particular, he says, "seemed like a pain in the butt."

Blake commented on Oranchak's video that it would be easy to enumerate the geometry of period-19 transposition into a computer program, but by that point Oranchak's videos received dozens of comments a day and Blake's mathematical suggestion was lost in the shuffle. But he kept at it until he found Oranchak's email address and proposed his idea directly. Oranchak was impressed, and invited Blake to join him in the hunt for a solution.

Oranchak began working on the 340 in 2006 and posted his first YouTube video on his efforts in April 2020. That first video debunked writer Robert Graysmith's proposed solution to the cipher, and in December that same year, Oranchak released the solution that he helped to obtain. That video has over 2 million views to date.

Using the University of Melbourne's supercomputer, Spartan, in conjunction with AZDecrypt, Blake and Oranchak parsed thousands of variations for the 340 cipher. Beyond period 19 and the knight's tour, they tried other arrangements, such as alternating the cipher's columns or organizing it along diagonal lines. Each new organization required multiple subvariations, such as moving each character 18 or 20 spaces instead of the traditional 19. It took hours, sometimes days, for AZDecrypt to churn through each possible solution. This methodology would've been impossible in 1969. "Homophonic substitution needs a really robust computer program," says Blake. "I was able to create many different candidate ciphers because I had access to Spartan."

Nevertheless, despite all the programming power at its gates, the cipher didn't yield. Occasionally, AZDecrypt would reveal a single word and compel the codebreakers to dig deeper, but everything led to a dead end. The team began breaking the cipher into sections and applying different solutions to different sections, but even that failed. Months passed. The team soon amassed over 650,000 tested variations, but no answers.

While Oranchak and Blake attacked the cipher, Van Eycke kept improving AZDecrypt. Oranchak wondered if they'd actually tried the right variation already but that it just hadn't been caught by an earlier version of the software. They began rerunning all 650,000 combinations again, with Oranchak hanging out in his wood-paneled office with the family's Labrador, watching the program and waiting for it to produce a viable solution. About halfway through the rerun, he spotted fleeting words and phrases that hadn't turned up during the first pass. In one variation, he found this fragment: *hope you are trying to catch me*. That seemed promising. Then he caught another phrase: *gas chamber*.

Oranchak used AZDecrypt's crib feature to lock in those words, the same phrase the Zodiac impostor had used on TV in 1969, and then continued rerunning the variations. Eventually the program cracked the first section of the cipher. "That's when I fell out of my chair," Oranchak remembers. "I think I scared my dog." The remaining two sections soon followed. They needed to be massaged and corrected in places, but at long last, the Zodiac's message emerged before the codebreaker's eyes:

I HOPE YOU ARE HAVING LOTS OF FUN IN TRYING TO CATCH ME
THAT WASNT ME ON THE TV SHOW
WHICH BRINGS UP A POINT ABOUT ME
I AM NOT AFRAID OF THE GAS CHAMBER
BECAUSE IT WILL SEND ME TO PARADICE ALL THE SOONER
BECAUSE I NOW HAVE ENOUGH SLAVES TO WORK FOR ME
WHERE EVERYONE ELSE HAS NOTHING WHEN THEY REACH PARADICE
SO THEY ARE AFRAID OF DEATH
I AM NOT AFRAID BECAUSE I KNOW THAT MY NEW LIFE IS
LIFE WILL BE AN EASY ONE IN PARADICE DEATH

MOST EXPERTS, including the FBI's crypto unit, agree that Oranchak and his team cracked the 340. Like the first cipher, it reveals a beguiling combination of high and low diction, spelling mistakes, and vague imaginings of immortality. Also like the first cipher, it lacks a hard clue as to the Zodiac's identity.

But James Fitzgerald says that even the 340's variations and mistakes hold valuable information for forensic linguists, including possible hints at the writer's race, ethnicity, age, and gender. Criminals are better at inserting purposeful mistakes than at hiding lifelong linguistic habits. In the case of the 340 cipher, Fitzgerald believes the Zodiac tried to upgrade his language to look more sophisticated than he is, by way of antiquated diction like "all the sooner" and "paradice."

He also suggests that both ciphers contain contraindicators, or statements that represent the opposite of what is true to the Zodiac. In other words, Fitzgerald asserts that the Zodiac never hunted wild game, never or rarely had sex, and was, in fact, terrified of dying. "Bottom line, Zodiac killed for thrill," he says. "It was mentally, physically, and sexually empowering for him, all of which were missing from his everyday life. The ciphers only added to the thrill, once the killings became routine." Fitzgerald predicts that behavioral scientists at the FBI will glean more information through further study of the ciphers.

Jim Clemente, a former FBI profiler, agrees. "Zodiac is nothing more than a vulnerable narcissist," he says. "He was attempting to show how smart he is [through the ciphers], but he's actually giving us evidence to take him down."

THE CODEBREAKERS
The Comprehensive History of Secret Communication from Ancient Times to the Internet
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DAVID KAHN
GANG SECRET CODES: DECIPHERED
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CRYPTANALYSIS
a study of ciphers and their solution
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LABORATORY DIVISION

Top: Materials from Oranchak's collection of cryptography texts. Oranchak, Blake, and Van Eycke combined their skills in programming and mathematics with their interest in traditional cryptography to solve the 340 cipher. Above: After solving the cipher, Oranchak, Blake, and Van Eycke received medals from the FBI's cryptanalysis unit.

> "IN HIS ZEAL TO CREATE A MORE DIFFICULT PUZZLE, THE ZODIAC DELIVERED A CIPHER ALMOST IMPOSSIBLE TO SOLVE."

The mechanisms of the 340 itself possibly reveal the Zodiac's limitations as a code writer. The cipher follows a variation of the knight's tour and period-19 transposition, but the alterations to each of these schemes are idiosyncratic and sloppy. "We almost didn't find the solution because of them," Oranchak says.

Francis Heaney, a puzzle expert, calls the 340 a "read-my-mind" puzzle. "Basically, [it's when] you've got an idea for a puzzle and there's no way to solve it unless the person has the same idea," Heaney says.

For example, the Zodiac altered his diagonal schematic in a seemingly random manner. He intended the six characters in the center-right of the cipher, which spell out "life is," to be extracted from the diagonal and added to the end of the translated cipher. There's precedent for that; some puzzles have "meta-answers," an extra step after computation to reach the complete puzzle's final conclusion (like when themed crossword clues must be rearranged to solve a riddle). But fair puzzles communicate the need for that extra step through what Heaney calls "breadcrumbs." The Zodiac left no such instructions. "There's not a lot of rhyme or reason to it," Heaney says of the 340. "It's a little bit free-form, which makes it very impressive that anyone solved it."

In his zeal to create a more difficult puzzle, the Zodiac overextended himself and delivered a cipher that was almost impossible to solve—not because of any masterful underlying mechanism, but because the cipher lacked a discernible logic and structure.

The best puzzles build incrementally upon themselves, explains Heaney. They may include multiple different steps, but those layers should be iterative. Zodiac's layers were haphazard at best. Solvable puzzles, even challenging ones, hint at their schematics through "flavor text"—proactive hints at a ski slope if, say, the puzzle follows a diagonal pattern. Heaney says inventive puzzlers also build difficulty through focus. The Zodiac sprawled in his methods, shifting the 340 abruptly between simple and homophonic substitution, utilizing multiple transpositions, and inserted a baseless meta answer. Based on the Zodiac's profile, particularly his relentless thirst for attention, he wanted his ciphers to be solved and his message of terror out in the world. These inconsistencies, in that context, constitute a failure.

Without the computing power of Blake's supercomputer and Van Eycke's AZDecrypt to overpower the Zodiac's unfair schematic, the 340 probably would have remained unsolved. And even though cracking the cipher revealed little biographical information about the killer, Oranchak thinks their methodology can lead to newer, faster ways of enumerating and substituting, which will allow other ciphers to be solved more quickly than under previous methods. "We live in an age of cryptography that is virtually unbreakable," Oranchak says. "But so are these old-school codes." Many unsolved puzzles continue to elude simple solutions, and some of these are connected to crime. "We need a better tool that can figure out what bucket a cipher belongs in before putting all that effort into breaking it."

Cryptological progress, Blake says, will require experts and intelligence agencies to think outside the box, collaborate and crowdsource, and be willing to test methodologies developed by amateurs and armchair detectives. That, says Mike Morford, author of *The Case of the Zodiac Killer*, is the single most exciting aspect of the 340 solution.

"It just proves that if you dig at something long enough and keep at it, whether it's for 40 years, 50 years, there's a chance that you can be part of the solution. These guys proved that," he says. "Their work encourages people to keep digging into these old cases and not to give up."

PETER MEANS/VTE (DAVID ORANCHAK, DETAILS); GETTY IMAGES (ZODIAC LETTERS, HARDEN, ENIGMA, FITZGERALD)

America's Most Fearsome Howitzer Has Entered the War in Ukraine

Can the highly maneuverable and massively powerful M777 overcome Russia's superior firepower?

BY HOPE HODGE SECK

EIGHT RESEARCH FELLOWS from the Pentagon-connected Rand Corporation published a report in 2019 detailing a frightening scenario that seemed increasingly likely: a Russian invasion of the NATO-member Baltic states—Estonia, Latvia, and Lithuania—that escalates to major war as the North Atlantic Treaty's Article 5 triggers full military response from the U.S. and other partner nations. Ground casualties in such a standoff would be devastating, the authors wrote, and a NATO victory far from assured, at least not without unacceptable losses.

Central to the report's more dire conclusions was the grim respect that Russian artillery commanded, from the country's BM-30 Smerch 300mm multiple-rocket launcher, with its 56-mile range, to the impressive and plentiful Russian 2S19 Msta 152mm howitzers. On that battlefield, the U.S. Army's artillery pieces would be outnumbered by the Russians' by a ratio of at least two to one.

"The United States and NATO must find ways to destroy, neutralize, or protect against these Russian fire capabilities," the researchers wrote, "and gain systemic, positional, and force advantages to allow them to defeat the Russian ground forces and win the conflict."

But numbers don't tell the whole story in a fight. One of the best U.S. counters to those Russian guns is the M777 howitzer. What this artillery piece lacks in range, it makes up for in agility, accuracy, and remarkable (for a giant gun) reliability—and since the first units arrived in Ukraine in April, it's the weapon that could be most decisive in helping Ukraine fight back against an assaulting Russia.

The towed 155mm cannons have already changed the dynamic of the war by providing necessary cover for Ukrainian infantry lines and answering Russian advances, destroying troop bridges, and delivering chaos from above. With nearly two decades of time served in war zones worldwide, the M777 is proving the enduring relevance of agile artillery on a modern battlefield.

As a journalist who has covered the Marines since 2009 and watched the M777 in action on multiple U.S. bases and during a night-fire mission in Afghanistan's Helmand Province, I can imagine the difference that 100 of these cannons might make in the artillery shootout that the Ukraine war in the Donbas region has become. Despite being smaller than Russia's monster howitzers, the "Triple 7" is still imposing.

The M777's narrow 17-foot barrel is mounted at the end with a towing eye and a boxy muzzle brake that serves to limit recoil. Sheathing the barrel are a dual recoil system and balancing gear, which provide stability and give the gun a bayonetlike appearance as it's aimed skyward. Its two-foot-long 155mm high-explosive rounds weigh 95 pounds each, are typically filled with a mix of RDX and TNT, and can be fired at enemy targets from up to 19 miles away.

That's the capability that Ukrainian forces need in order to defend themselves against Russia. By spring, the Ukrainian army had mostly repelled Russia from Kyiv, but that early offensive was followed almost immediately by an offensive in Ukraine's flat eastern Donbas region. Powerful Russian rocket and cannon barrages devastated cities like Mariupol on the coast of the Azov Sea and pinned down Ukrainian military positions. Though Ukraine has some of its own Soviet-era artillery weapons, it's been outgunned since the start of the conflict. Without any cover from terrain in the east, Ukrainian forces were forced to dig ditches and take cover behind tanks.

U.S. M777 howitzers have arrived in Ukraine and are in use on the front lines providing high-explosive weaponry and heavy artillery systems supplied by Western nations.

As Russian guns flattened towns in the Donbas, President Volodymyr Zelenskyy called on the West to provide longer-range weapons. The U.S. responded by announcing that it would send 126 M777 howitzers (along with some 200,000 rounds) to Ukraine inside two separate $800 million weapons packages. The power of the M777 was felt quickly by both sides.

"Dear Ukrainians!" Oleksii Yuriyovych Reznikov, Ukraine's minister of defense, wrote in a May 28 Facebook post published in Ukrainian and English. "The amount of feedback in the public space from our soldiers who have gained experience in using foreign-made heavy artillery is growing. I am glad that a lion's share of this feedback is extremely positive. Thanks to the skill of our defenders, the Russian occupiers are receiving a rebuff they did not expect."

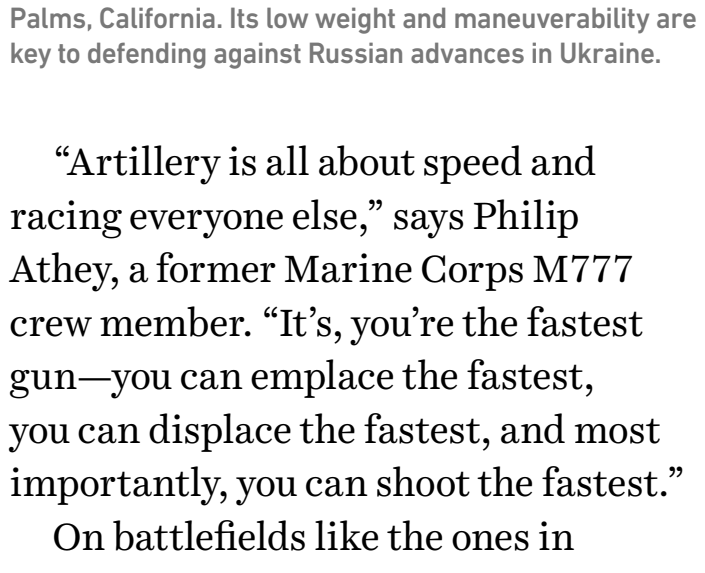
In early June, video shot by a Russian news crew showed the firing of a Russian TOS-1a, a 220mm multiple-rocket launcher with a range of about six miles. Within a minute, as footage continued to roll, Ukraine answered with accurate counter-battery fire from an unseen artillery weapon that nearly took out the Russian weapon.

★

THE M777'S ABILITY to disrupt, repel, and attack opponents stems from its light weight, maneuverability, and agility. Pound for pound, as boxers say, this is one of the most fearsome pieces of artillery in modern warfare.

At 9,300 pounds, the cannon weighs 40 percent less than its 150mm predecessor, the Rock Island Arsenal–designed M198, affectionately known as the "hernia maker" because of the strain it put on troops maneuvering it on the battlefield. In the thick black mud that covers the Donbas region, the Triple 7 can be towed on rutted roads that would bog down larger vehicles and artillery pieces. The Ukrainians' 2A65 "Msta-B" 152.4mm towed howitzer, by comparison, weighs about 15,000 pounds.

This ultralight quality enables the M777 to be transportable via sling underneath a CH-47 Army Chinook or Marine Corps MV-22 tilt-rotor Osprey, or like cargo inside any of the Air Force's airlift transport planes. It also shaved minutes off emplacement and displacement time—the time it takes a gun crew to stabilize a gun for firing and then secure it for transport. As a result, well-trained crews can complete those processes in about three minutes each. In a counter-battery fight, where cannon crews are working to "shoot and scoot"—that is, deliver rounds and then race to a new location before enemy radars locate their position for targeting—mobility and speed are king.



A Marine Corps CH-53 Super Stallion helicopter lifts an M777 howitzer during a training exercise at Twentynine Palms, California. Its low weight and maneuverability are key to defending against Russian advances in Ukraine.

"Artillery is all about speed and racing everyone else," says Philip Athey, a former Marine Corps M777 crew member. "It's, you're the fastest gun—you can emplace the fastest, you can displace the fastest, and most importantly, you can shoot the fastest."

On battlefields like the ones in Ukraine's Donbas region, speed and maneuverability allow infantries to advance or defend a position by constantly repositioning their howitzers and then rapidly setting them up to fire again.

Retired Army Major General Mark McDonald, former commander of the Army's Fires Center of Excellence and current president of the U.S. Field Artillery Association, explains how well-trained crews do this: "While one howitzer is fired, others should be advancing and moving into position, to keep the enemy's head down and avoid becoming a sitting target," he says.

This is an advantage cannons have over higher-maintenance rocket launchers: "Because you can fire 200, 300 rounds in a day. The crew will be exhausted, but you can do it."

★★

THE BATTLE FOR artillery supremacy between the M777 and its Russian counterparts is shaping the war in Ukraine—almost exactly as the Rand researchers had predicted. And their grim warnings have proved prescient: Russia's heavy artillery, with its greater size and range, is a formidable opponent.

Russian artillery forces have another appreciable advantage: history. On a battlefield overflown by sophisticated combat drones guided by artificial intelligence, artillery recalls a more ancient form of warfare, one Russia has continued to invest in while other nations have moved on to smarter, more advanced weapons. The M777, with all its advantages and disadvantages when compared with modern Russian artillery, reflects those divergent interests.

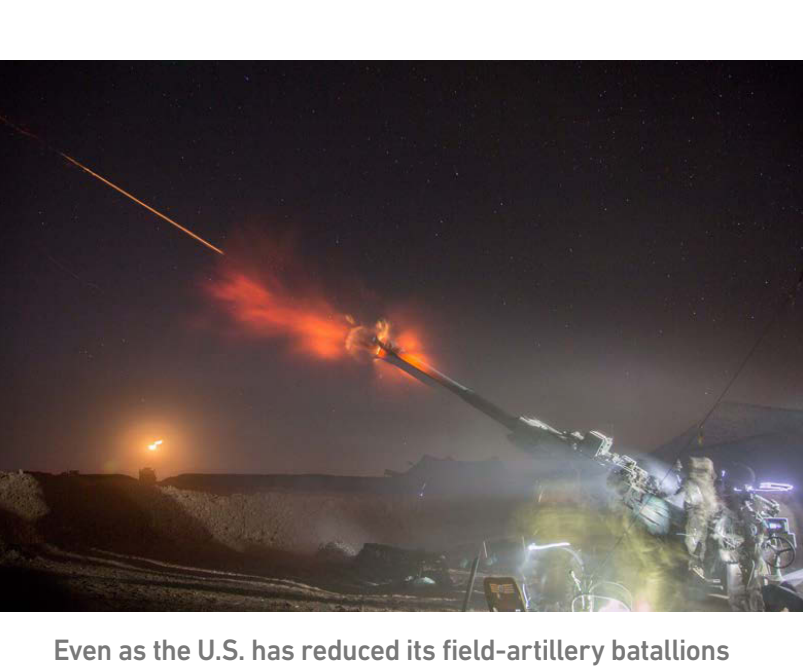
Cannons date back to the Middle Ages, when they were first used as siege weapons. Then, as today, they were powerful but short-range artillery used most effectively when the forces using them could see the enemy they were targeting. The howitzer (its name is derived from the German word *Haubitze*, or slingshot) appeared on battlefields during Europe's Hussite wars in the 1420s and 1430s. Unlike the cannon, it used a shorter barrel and shot rounds farther, with a higher arc. Crucially, that greater range allowed armies to fire at enemies they could not directly observe.

> "WHILE ONE HOWITZER IS FIRED, OTHERS SHOULD BE ADVANCING TO KEEP THE ENEMY'S HEAD DOWN."

The first widely used U.S. Army howitzer, a 12-pound gun called the mountain howitzer, entered service in 1841. Designed to be light and capable of long-range strikes due to a short barrel and back-sloping breech, the weapon saw service in the Indian and Civil Wars. From there, howitzers became sturdier, farther-ranging, and more accurate thanks to more rugged alloys, better-engineered barrels, and more powerful ammunition. The U.S. was using 155mm cannons by World War I with its version of the French-made 1917 Schneider, which boasted a range of seven to 10 miles—about 15 times that of the mountain howitzer. In 1918, the U.S. Army field artillery fired the final shot of World War 1 from a howitzer it called "Calamity Jane."

The increased size, range, and mobility of field artillery hasn't significantly altered its value on the battlefield: These big guns remain most effective when enemies fight across clear battle lines, or when a force launches a "shock and awe" battle campaign or invasion. Those looking to pinpoint a recent apex of U.S. field artillery might look to February 1991, during Operation Desert Storm, when more than 350 U.S. Army artillery weapons targeted Iraqi positions, thwarting counterattacks and helping to secure a swift victory.

During the two decades that followed those battles, big guns took a back seat as the U.S. shifted focus to counterinsurgency efforts during its protracted war in Afghanistan and ongoing fighting in Iraqi cities. Between 2003 and 2016, according to the authors of the Rand report, training and readiness for Army field artillery atrophied as the service reduced its active field artillery battalions by nearly half, from 96 to 50. It was during the start of this drawdown, in 2005, that the U.S Army first used the M777 in combat, and it would be another decade before the artillery could prove its full value in battle.



Even as the U.S. has reduced its field-artillery batallions in favor of smarter weapons systems, the M777 has played important roles in operations against ISIS, like this night-fire mission outside of Mosul, Iraq, in 2016.

Russia, on the other hand, never slowed its investment in artillery.

The armies of what is now Russia have a history of using artillery in battle that dates back to the fourteenth century. In the early nineteenth century, Russia deployed an impressive 12-pound cannon during the Napoleonic Wars, which took place 50 years before the U.S. Army developed its mountain howitzer. Soviet deep battle theory, popularized by Soviet Union Marshal Mikhail Tukhachevsky in the 1930s, emphasized inflicting devastation on the enemy not just on the front lines, but also to the far reaches of the battlefield. This was accomplished in part by teaming infantry, tanks, and artillery for a shock effect that allowed Soviet troops to break through enemy defenses and then push farther in to cause disorder and destruction.

"The signature Soviet move for a large-scale offensive in the Great Patriotic War, which is what they called World War II, was the massive artillery barrage," says Scott Boston, a senior defense analyst at the Rand Corporation and a coauthor of the 2019 report on Russian aggression. Boston is a former U.S. Army field artillery officer whose research includes an emphasis on Russian ground capabilities.

When the Soviet Union launched its successful assault on Berlin in 1945, it had positioned some 375 guns and mortars for each kilometer of front. "We're talking thousands of guns and rocket launchers and mortars," Boston says. The Battle of Seelow Heights, as the siege is now known, has been recognized as one of the largest artillery bombardments in history.

Russia's invasion of Crimea in 2014 shocked Western observers and highlighted the strength of its artillery weapons, which have reportedly been responsible for 80 percent of battle casualties. The 9K720 Iskander short-range ballistic missile system, capable of firing over 300 miles, has no parallel among U.S. and NATO systems, according to the authors of the Rand report.

"The Russian Army has deployed large numbers of cannons and rocket launchers at the brigade and battalion tactical group levels," they wrote. "When combined with a growing, multifaceted targeting and reconnaissance capability, Russian artillery is a formidable potential opponent."

Countering that opponent is a daunting task for the M777 and its crews. But there's evidence that the howitzer can deliver with its speed, precision, and agility. After years of mainly firing illumination rounds in Afghanistan to flush out insurgents in the hills, the M777 took on a prominent combat role for the first time in the fight against ISIS. In 2017, U.S. forces waged a battle to retake the city of Raqqa, one of the terrorist group's last remaining holdouts.

Marines and cannons were dispatched from amphibious ships to provide fire support for U.S.-backed ground forces that entered the city for close combat. For five months, a single Marine battery laid down indirect fire on ISIS positions in and around the city, firing more than 35,000 rounds and blowing out two gun barrels from overuse in the process. By comparison, as the *Marine Corps Times* reported, about 34,000 155mm rounds had been fired by the entire U.S. military during the 2003 invasion of Iraq. The battle proved the outsize effect a small artillery contingent can have, if it's well supplied and skillfully operated.

★★★

THE M777 BEARS a close family resemblance to the U.S.-made 155mm guns of World Wars I and II, although it is less stocky and more powerful and fires with greater accuracy. Though the M777 is commonly described as "ultralight" relative to its foreign peers and predecessors, that adjective belies its power.

While reporting on Marine weapons systems, I've stood beside the gun as it was loaded and fired in training. At the Marine Corps Air Ground Combat Center Twentynine Palms in California, home to one of the few ranges that can safely accommodate the weapon, Marine officers told me they always alerted the local airport whenever they planned to shoot, because rounds flew high enough to disrupt air traffic.

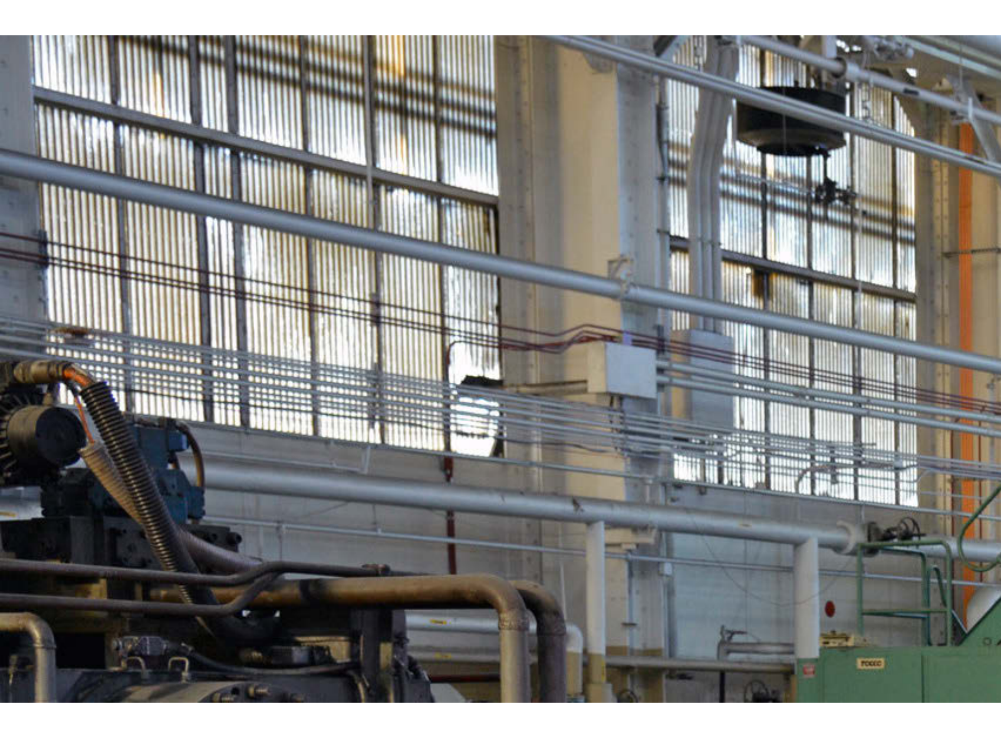
> "EVEN STANDING AT A SAFE DISTANCE, YOU FEEL THE WALLOP DEEP IN YOUR CHEST."

The skies free of planes, I watched as the Triple 7 was towed into position on two wheels via a seven-ton military truck; then it was stabilized via its flat titanium "spades," which the crew manually buried with rocks and earth to further secure it. What followed was a shouting, chaotic ballet of motion. The clank and ratchet of metal on metal and the thunk of a round being rammed into the breech all recalled the mechanics of ancient cannon and trebuchet, despite the advanced targeting hardware.

Today's M777s fire one round at a time, a maximum of five rounds per minute. Even standing at a safe distance, you feel the wallop deep in your chest. The force of the shot pushes the cannon back about two feet into the dirt, despite equipment that mitigates recoil. Military artillery specialists are at notoriously high risk for hearing loss, a hazard exacerbated by the refusal of some to wear hearing protection. Seventeen weeks pregnant on the range at Twentynine Palms in 2015, my ears plugged with "foamies" and my torso securely covered by a flak jacket, I wondered if my unborn daughter sensed the vibrations too.

General George S. Patton, the legendary commander of the Third Army in World War II, famously called field artillery "the King of Battle." To encounter a 155mm cannon is to respect it. The heir to that battlefield throne, the M777, owes its enviable power-to-weight ratio to a precision manufacturing process developed over decades. By the time the hefty M198 entered service in 1979, Army leaders already knew they wanted a system light enough to arrive on the battlefield from the air, and they began seeking a way to get that without sacrificing range.

The design began in the 1980s with concepts from Vickers Shipbuilding and Engineering, a British company that was later bought by the U.K. defense giant BAE Systems. The material, titanium Ti6AI4V alloy, had to be able to take the stress of cannon fire and recoil without warping or breaking down—the Army and Marine Corps standard calls for an average of 900 rounds fired between anomalies that force a stop in operations—and undergo a 20-year corrosion test, according to the trade publication *Azo Materials*.



A 155mm howitzer tube is en route to the rotary forge after leaving an arsenal furnace where it was heated to nearly 2,000°F. After cooling for approximately 15 minutes, the tube will be near the finished shape of a howitzer barrel.

The howitzers initially had all-steel barrels but were upgraded with full-bore chrome-plated tubes in the mid-2010s. These limited the buildup of residue inside the cannon, and that upgrade has reportedly extended their service life by as much as 300 percent. That matters, because every 100-pound round sent downrange brings a cannon barrel closer to its point of failure. Heavy use, such as in the current prolonged artillery duel in the Donbas region, can blow out a gun tube fast.

The howitzer owes its reliability to another factor: Every single 17-foot-long tube is produced by a single forge at Watervliet Arsenal. The 200-year-old plant, just north of Albany, New York, has made every Army gun barrel for nearly 50 years. Inside the facility, a rotary forge turns red-hot preform hunks of steel and alloy, using mechanical hammers to draw out precise shapes and contours. Each hammer strike applies roughly 200 tons of pressure. Before a barrel is deemed combat ready, Watervliet applies a minimum of 900 tons of pressure and then runs hydraulic fatigue tests that simulate firing 1,000 rounds through a barrel in a day.

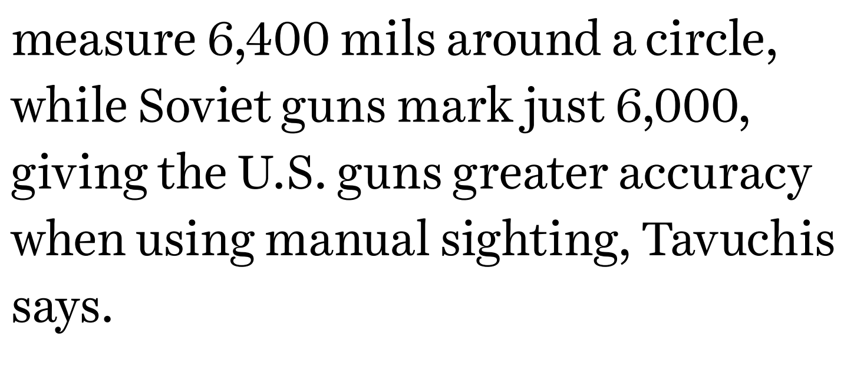
"It's like the world's largest *Forged in Fire* episode," says Rand Corporation analyst Boston, who has toured Watervliet. "They actually try to do everything they can to give these howitzer barrels the best possible service."

★★★★

B**Y EARLY MAY**, Ukraine's military focus had fully shifted from defending Kyiv and other cities to engaging Russia in the eastern regions of the country, where Russia had amassed much of its army. Tactics shifted too. Heavy artillery began to dominate the action as the armies attacked each other from miles apart without ever seeing the enemy. The M777s had arrived just in time.

Maneuvering quickly through the spring mud, they delivered accurate strikes against Russian targets. In early 2016, precision-guidance fuze kits began arriving at M777 units, allowing them to cut back the margin of error for the standard high-explosive round from 200-plus meters to under 30.

Many M777s use a digital fire-control system that allows precise targeting with the aid of computer tablets. But the howitzers shipped from the U.S. to Ukraine did not include those computer-aided systems, says Chris Tavuchis, a retired Marine Corps colonel who commanded the U.S. Marine Artillery Detachment at Fort Sill, Oklahoma, from 2019 to 2021. He believes Ukrainian forces are using the artillery's manual targeting system, which requires crews to calculate distance via small increments marked on the weapon sight known as milliradians, or mils. Even without the computer-aided targeting, the M777s have an advantage. Their sights measure 6,400 mils around a circle, while Soviet guns mark just 6,000, giving the U.S. guns greater accuracy when using manual sighting, Tavuchis says.



When firing the GPS-guided XM982 Excalibur round, the M777 can hit targets 25 miles away with an accuracy of five meters. But those rounds cost a staggering $70,000 each.

The most common M777 shells are high-explosive rounds that have a blast radius of approximately 70 meters. That makes the conversation about precision somewhat relative. But when forces do require greater accuracy, they have options. Ukraine likely received some Raytheon-made M982 Excalibur rounds, which extend firing range out to 25 miles thanks to stabilizing fins, and use embedded GPS to reduce error at that distance to five meters or less. But the Excaliburs cost about $70,000 per round, compared to less than $1,000 for a standard HE round.

Even precision rounds don't fully address the greatest criticism against heavy artillery: It's a weapon that creates craters in the earth, not an assassination tool. While Marines bragged that in Raqqa the M777s had "killed more ISIS than anyone," Amnesty International and other groups decried the use of indirect fires in urban areas, contending that collateral damage had claimed the lives of an estimated 1,600 civilians.

As Russian and Ukrainian cannon crews fight near towns inside the Donbas region, the civilian casualty toll is already climbing; international organizations overwhelmingly fault Russia with the worst offenses. Having pulled back from Kyiv, Russia sought to dominate territory and towns in the east in a devastating scorched-earth campaign, and Ukrainian victory is by no means assured. In late June, amid heavy artillery fire and intense urban fighting, Russia took the major city of Sievierodonetsk.

But the victory didn't come easily. As the ground battles intensified, heavy artillery like the M777 played an increasingly decisive role. Earlier, in May, video emerged of M777s raining shells downrange in Ukraine, stalling Russian forces as they attempted to cross the Siverskyi Donets River to reach Sievierodonetsk on the other side. They found themselves surrounded instead by Ukrainian artillery, which shredded their pontoon bridges, laid waste to tanks and weaponry, and left more than 400 Russian soldiers dead. U.S. M777s were on the defensive line, Colonel Dmytro Kashchenko, the Ukrainian officer who commanded the effort, told the *New York Times*.

Later in the month, the General Staff of the Armed Forces of Ukraine announced that M777s had scored five direct hits on the pontoons and took as many as 40 tanks and armored combat vehicles out of action, firing from a distance of about 12 miles. Ukrainian officials also suggested that Ukrainian targeting was superior to that of the Russians, saying they'd suppressed enemy batteries with just 10 to 12 shells, while their foes had fired more than 48.

While M777s are unlikely to send the Russian army into retreat on their own, they're delivering a punishing response to invaders with unclear objectives. And the Ukrainian army, which has reportedly been identifying artillery targets via drone and using camouflage to conceal the weapons from the enemy, seems determined to use them to maximum advantage.

"It's a very capable weapons system. And we're getting enough of the systems and enough ammo in their hands to be able to make a difference," McDonald, the retired major general, says of the M777. "In artillery, overwhelming firepower is very important." PM

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