Issue Brief

Defending the Ultimate High Ground

China's Progress Toward Space Resilience and Responsive Launch

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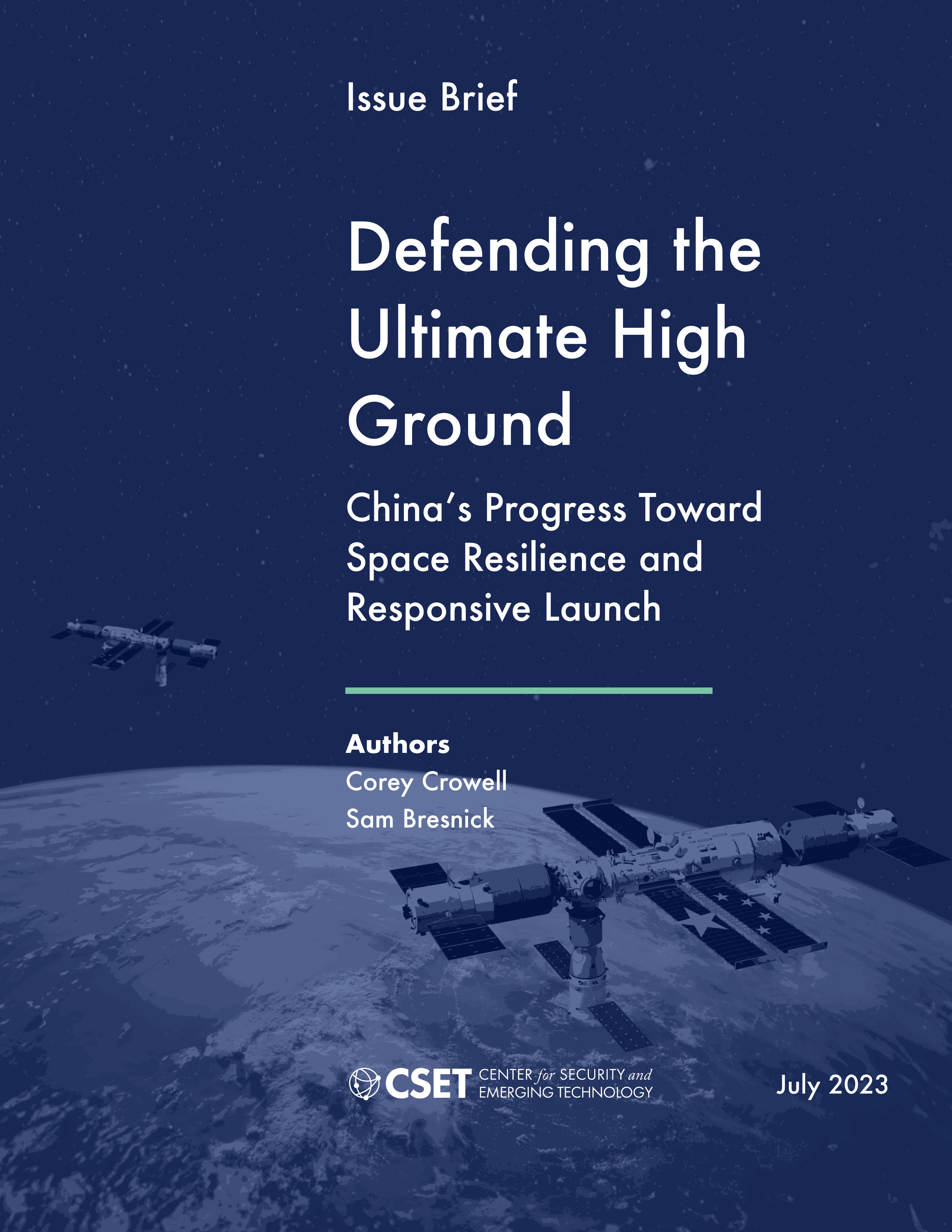

CSET CENTER *for* SECURITY *and* EMERGING TECHNOLOGY

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Executive Summary

The United States and China recognize the strategic importance of space and are seeking to better utilize satellite systems. Both countries have built extensive space architectures, and they now depend on space-based assets for a wide range of economic, scientific, and military applications. Hence, Washington and Beijing are working to better protect their respective space architectures by making their satellite systems more resilient to attack while also taking actions to deter attacks against those systems.[1]

Unlike those of the United States, China's space architecture resilience objectives are unknown, and it cannot be assumed that Beijing is approaching space resilience in the same way as Washington. That said, it is possible to better understand China's progress toward improving its space resilience through an assessment of its actions using open-source data, and through the lens of what the United States considers critical in this area. This approach has its limitations; while imperfect, it can nonetheless provide insights on China's progress using metrics both important and familiar to U.S. military leaders and policymakers.

Space architecture resilience is a broad concept that is difficult to fully define and even more challenging to measure. However, U.S. military leaders have identified objectives to improve space resilience, and this paper evaluates China's progress across four of these objectives: disaggregating space-based capability through satellite proliferation, diversifying orbital locations where satellites are placed, increasing access to space through a robust launch industry, and developing the ability to quickly launch satellites in response to need, a capability known as tactically responsive space launch (TRSL).

The analysis relies on publicly available data on orbital-class launch vehicles, space launch events, and the number and location of satellites placed in orbit. Sources include the United Nations Office for Outer Space Affairs (UNOOSA), CelesTrak, and Gunter's Space Page. Alongside assessing China's developments in these areas, we include brief comparisons with the United States' progress across the aforementioned four dimensions. Key findings include:

- China is rapidly expanding its space architecture. According to CelesTrak, in the past four years alone, China has nearly doubled the total number of satellites it has placed in orbit since first successfully launching a satellite in 1970. Of the

842 Chinese satellites placed in orbit from 1970 through 2022, 419 have been launched since 2019.[2]

- China is placing its new satellites in a diverse set of orbital regions. China continues to expand its presence in more traditional orbits such as low Earth orbit (LEO), medium Earth orbit (MEO), and geosynchronous orbit (GEO), while also positioning satellites in less common regions. In 2018, China placed the Queqiao communications satellite in cislunar space beyond the Moon, the first of its kind in this region of space.[3] In 2021 and 2022, China placed two Shiyan experimental satellites in Molniya orbits, its first uses of the unique elliptical orbit that offers extended coverage over Earth's North Pole.[4]

- China is accelerating its launch pace and expanding its launch industry. In the past six years, China has doubled the total number of orbital-class launches since its first in 1970. Of the 505 Chinese launches from 1970 through 2022, 249 have occurred since 2017.[5] To enable the faster launch tempo, China has constructed a fourth launch complex and introduced five new liquid-fuel and 11 new solid-fuel launch vehicles during the past decade (2013–22).[6] Several of these launch vehicles include multiple variants.

- China has prioritized the development of a TRSL capability designed to quickly launch satellites in the event of an emergency.[7] China is leveraging several of its new mobile, solid-fuel launch vehicles to provide this capability and has performed multiple demonstrations since 2013.

Beijing has demonstrated rapid progress in each area assessed for this study, and China appears to have surpassed the United States in one specific measure of space resilience: TRSL, which would be needed in the low-likelihood, high-consequence scenario that crucial mission-supporting satellites must be quickly replaced. Beijing has bolstered its TRSL capabilities through investments in comparatively small, mobile, solid-fuel launch vehicles, which can be launched faster than larger, liquid-fuel rockets that depend on extensive launch infrastructure. Beijing performed its first successful demonstration of such a launch vehicle, the Kuaizhou-1, in 2013, and has since continued to expand its fleet of mobile, solid-fuel rockets and conducted dozens of such launches.[8] Meanwhile, the United States has performed only one stated TRSL demonstration, which took place in 2021.[9] It has planned a second test for later this year.[10] The United States has the most advanced space industry in the world, but it has not demonstrated a commensurate ability to launch rockets on short notice.

To address its TRSL capability and close the gap with China, the United States should consider:

- Developing strategies to produce and manage stored inventories of satellites, as well as prioritizing technical designs that enable satellites to be removed from storage and launched on short notice. TRSL requires that satellites and launch vehicles be kept in near ready-to-launch states. Satellites maintained in storage and designed for rapid launch would minimize the time required to reestablish a degraded on-orbit capability.

- Increasing investments in solid-fuel launch vehicles. A TRSL approach similar to that of China—using storable, mobile, solid-fuel launch vehicles—would require new investments in solid-fuel launch vehicle technology with a focus on storability, mobility, minimizing required ground support equipment, and rapid launch capability.

- Partnering with commercial launch providers to develop and maintain liquid-fuel launch vehicles able to meet TRSL objectives. Though most commercial, liquid-fuel rockets are not designed to launch on short notice, commercial and government interests in reducing launch preparation timelines may be aligned, and the commercial space industry is already exploring how to quicken its launch pace.

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Introduction

Since the late 1950s, the United States has viewed space-based capabilities as essential to safeguarding its national security. Though Sputnik and the race to the Moon attracted the most attention, U.S. scientists began launching early missile warning; navigation; and intelligence, surveillance, and reconnaissance (ISR) satellites in the late 1950s and early 1960s alongside the National Aeronautics and Space Administration's Moon missions.[11] Washington completed its first communications satellite constellation in the late 1960s, and it began constructing the Global Positioning System (GPS) in the 1970s to provide position, navigation, and timing (PNT) for military and eventually civilian applications.[12]

Concerns over conflict with the Soviet Union drove many of these advances, but the 1990-1991 Gulf War was the first conflict during which the U.S. military leveraged its full suite of space-based technologies, enabling a decisive victory in what is now considered the first "space war."[13]

Since then, advances in satellite technology and an expanding space launch industry have led the U.S. military to increasingly rely on space-based capabilities to support warfighting operations. Today, satellite systems provide the ISR, PNT, early missile warning, and communications capabilities that magnify the U.S. military's ability to project power in all domains (air, sea, land, cyber, and space). ISR satellites collect data across the globe, and communications satellites move that data to military and civilian leaders in near–real time.[14] PNT satellites help guide personnel and weapon systems to their desired locations, enabling capabilities such as precision strike.[15] Early missile warning satellites are designed to detect nuclear-armed intercontinental ballistic missiles (ICBMs) within seconds of launch, passing that information to missile defense systems such as Ground-Based Midcourse Defense, meant to intercept ballistic missiles in flight.[16]

Space-based assets have become critical inputs to many of the military's new development efforts including unmanned air, sea, and ground vehicles, which often rely on PNT satellites for positioning information and on communications satellites for remote command and control. A more specific example, the Joint All-Domain Command and Control (JADC2) concept, aims to collect, process, and exploit data across all military services through a unified network, and pass that information to decision-makers.[17] ISR satellites will be an important source of data for JADC2, and communications satellites will enable data distribution within the JADC2 network.

Unmanned vehicles and the JADC2 concept represent just a few examples of how robust space capabilities can amplify warfighting operations.

Recognizing the need to consolidate and coordinate space acquisitions and operations, the United States created a new military branch, the United States Space Force, and reestablished United States Space Command in 2019.[18] The U.S. government tasked the USSF with building, launching, and operating space systems that further enhance joint warfighting capabilities, and USSPACECOM with protecting and defending these systems in an increasingly contested space domain.[19]

China's Transition to Space-Enabled Warfare

Though China has not fought a war since 1979, Beijing is increasingly integrating space-based capabilities into its military doctrine. From the early days of the People's Republic of China, Beijing has viewed space as both a forum for great power competition and a domain of economic and military opportunity. In trying to keep pace with the United States and Soviet Union, Mao Zedong formally launched the "Nuclear Bombs, Ballistic Missiles, and Earth Satellites" program in 1958, linking the development of nuclear weapons and ICBMs with the construction of a satellite, which was successfully launched in 1970.[20] Since then, Beijing has developed dozens of space vehicles and launched hundreds of satellites, which, according to China's 2021 space white paper, will help "defend national security, lead self-reliance and self-improvement efforts in science and technology, and promote high-quality economic and social development."[21]

Space capabilities are now playing a pronounced role in security affairs. As China has rapidly modernized, the People's Liberation Army has improved its capabilities not only on land, at sea, and in the air, but also in the cyber and space domains. Although the PLA has historically concentrated on strengthening its traditional military assets, the past 30 years have seen the Chinese military emphasize the importance of space systems in order to bolster its operational competencies and develop world-class warfighting capabilities.

China has been developing space launch vehicles and satellites since the late 1950s, but it was not until the Gulf War in the early 1990s that the PLA fully realized the operational and strategic benefits of advanced satellite networks. After analyzing the U.S. armed forces' integrated, satellite-enabled operations during that war, the PLA released its "Military Strategic Guidelines for the New Period," which noted that its armed forces must be prepared to fight "local wars under modern, high-tech conditions."[22] The guidelines specified that the PLA needed to better integrate satellites into its war plans, as Chinese analysts were surprised by the pronounced role U.S. satellites played in intelligence gathering and data transmission during the Gulf War.[23]

Chinese military doctrine has evolved to emphasize the importance of utilizing information in modern combat operations. The PLA's 2004 white paper noted the need to "win local wars under the conditions of informatization," while the 2015 version stated China's goal of "winning informatized local wars," or triumphing in modern, high-end conflicts near the Chinese mainland.[24] Such conflicts demand enhanced gathering, transmission, and analysis of information, which the PLA is accomplishing through the development of ever-more capable satellites and their integration into its operational concepts. For the Chinese military, using satellites to dominate the information sphere in space, as well as controlling and exploiting information flows, is an important aspect of winning informatized wars.[25]

Beyond information exploitation, China has poured resources into developing its space capabilities for ISR, command and control, and precision navigation and targeting, including through the establishment of the PLA Strategic Support Force, a new military outfit that oversees space, cyber, and electronic warfare.[26] Since 2015, China has increased the tempo of satellite launches, provided more resources to the private sector for launch-vehicle research and development, and published more precise policy guidance on space-related activities. [27] Beijing now operates more than 250 ISR satellites, including those that can observe radar and radio communications,[28] which help the PLA monitor, and potentially target, foreign militaries or other assets operating both in the Indo-Pacific and farther afield.[29] Beijing has also developed a fledgling network of early warning satellites that it hopes would detect incoming missiles.[30]

On top of its ISR capabilities, China operates dozens of communications satellites, including several that are used explicitly by the military.[31] The PLA views such systems as essential for guaranteeing the real-time communications and data flows needed for situational awareness and coordinated, multi-domain operations,[32] not to mention for supporting their military personnel operating or based in locations far from China, for instance the Western Pacific and Djibouti.[33]

Complementing these communication capabilities is Beijing’s mobilization of PNT satellite technology. The BeiDou Navigation Satellite System (北斗卫星导航系统) now boasts 55 spacecraft in orbit.[34] BeiDou is Beijing’s version of GPS, and its improving accuracy has allowed China to eliminate its reliance on the American PNT service, as well as to provide other countries with an alternative to U.S. GPS.[35] These capabilities, combined with China’s ISR assets, could eventually enable it to manage a globally operating force and carry out longer-range precision strikes, increasingly important capabilities for Chinese international ambitions and 21st century warfare, respectively.[36]

Indeed, Chinese military academics consider space the “central pillar” for future operations, as well as a key enabler of China’s transition from a “mechanized” to an “informatized” and “intelligentized” fighting force.[37]

Through the integration of PNT, ISR, and communications satellites, the PLA believes it will be able to link its ground, sea, air, nuclear, cyber, electronic warfare, and space assets in service of multi-domain operations. These combined capabilities are an essential component of the PLA's new Multi-Domain Precision Warfare (多域精确战) concept, which envisions using such capabilities to coordinate joint force precision strikes against enemy systems.[38] MDPW, China's answer to the U.S. JADC2, is, in turn, a key feature of the PLA's system destruction warfare (体系破击战) concept, a doctrine based on identifying, degrading, and destroying an adversary's operating systems.[39]

If executed as the Chinese military envisions, system destruction warfare could lead to shorter wars, as the goal is to disrupt information flows and paralyze enemy war-fighting capabilities.[40] Thus, it is clear why Beijing has made space warfare a focal point of its military modernization. Moreover, because the PLA believes that disrupting an adversary's space operations is a critical part of MDPW, it has developed a suite of counter-space capabilities, including missiles, lasers, and space robots.[41]

Similarly to the U.S. military, the PLA's increasing dependence on space-based capabilities has led it to further invest in defending critical space-based assets, as well as to develop capabilities that hold other countries' satellites at risk.

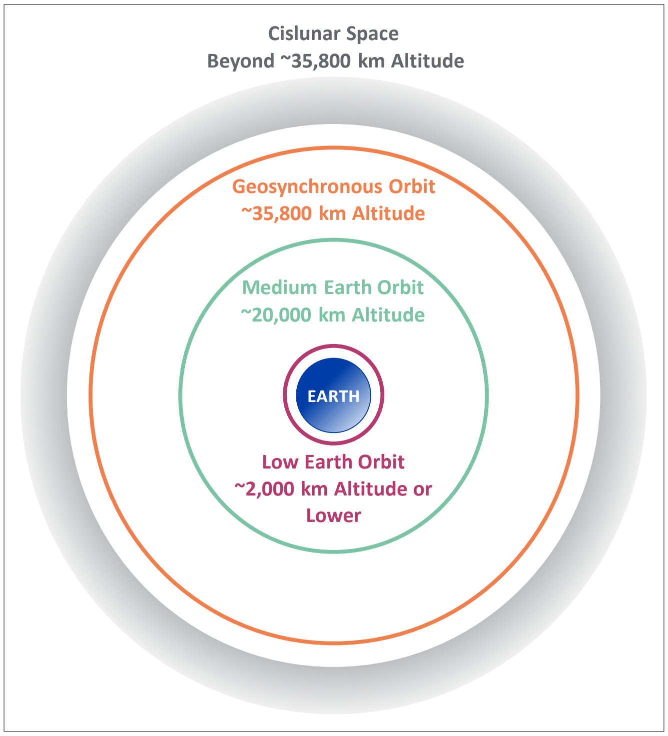
Threats to Satellites

In addition to the United States' and China's increasing commercial and military reliance on space-based capabilities, both countries, as well as Russia and India, have successfully demonstrated the ability to intercept and destroy satellites in low Earth orbit (LEO).[42] In its 2022 annual threat assessment, the U.S. intelligence community highlighted China and Russia's efforts to field new anti-satellite weapons (ASATs) intended to target U.S. and allied orbital systems.[43]

ASATs were originally designed to defend against the possible deployment of space-based nuclear weapons.[44] Even after the 1967 Outer Space Treaty banned orbiting nuclear weapons, however, ASAT development continued.[45] Modern kinetic ASATs consist of precision-guided devices that destroy satellites simply by making contact at very high speeds.[46] While effective, these ASATs produce thousands of pieces of debris that, depending on the target satellite's altitude, could remain in space for decades, threatening other satellites.[47]

Russia's kinetic ASAT test in November 2021 created 1,500 trackable pieces of debris, and, in October 2022, the International Space Station had to maneuver to avoid a piece of debris from the test.[48] But not all ASATs are kinetic. Electronic warfare, cyber-attacks, and directed energy weapons, both ground- and space-based, can temporarily or permanently disable a satellite, or just its sensors, and can be as effective as kinetic ASATs.[49]

Figure 1. Earth's orbital regions.*



Until now, kinetic ASATs have only been used to target and destroy satellites in LEO.[50] By using more powerful rockets, however, kinetic ASATs could be boosted to higher orbits, threatening satellites in medium Earth orbit (MEO), geosynchronous orbit (GEO), and even into cislunar space (see Figure 1).[51] Several countries, including China and Russia, have developed and tested electronic warfare and directed energy weapons intended to damage or disable satellites.[52] These non-kinetic weapons are more difficult to attribute and provide attack options that are less escalatory than kinetic ASATs. Though LEO satellites are most at risk from these current threats, future satellite constellations, even those that will use higher orbital regions, should be resilient to all types of ASAT attack.

Components of a Resilient Space Architecture

The confluence of growing reliance on satellites for military operations and an increasing ASAT threat have led the United States and China to prioritize construction of space architectures that can better withstand kinetic and non-kinetic ASAT attacks. Space architecture resilience is a broad concept that is difficult to fully define using any single set of objectives or components. That said, during a January 2023 forum on space acquisition, Frank Calvelli, the Assistant Secretary of the Air Force for Space

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[*] LEO ranges from ~160 km to ~2,000 km. GEO is 35,786 km. MEO covers the entire region from above LEO to below GEO but is simplified in Figure 1 as ~20,000 km, the approximate altitude of GPS satellites. Cislunar space covers the region above GEO and extends to approximately Earth-Moon Lagrange Point 2, just beyond the Moon's orbit.

Image source: Laura Duffy and James Lake, "Cislunar Spacepower The New Frontier," *Space Force Journal*, December 31, 2021, https://spaceforcejournal.org/3859-2/.

Acquisition and Integration, noted that the United States could improve space architecture resilience through proliferating satellites, “diversif[ying] orbits, integrating commercial capabilities,” and developing the capacity to reconstitute space-based assets.[53] Building on Calvelli’s objectives, we argue that a resilient space architecture consists of, but is not limited to, the following 10 components:

- Constellations that:
    - disaggregate missions across numerous satellites
    - consist of diversified orbital regions (LEO, MEO, GEO, cislunar) for satellites performing similar missions
    - include reserve on-orbit capacity
    - comprise satellites with improved maneuverability
    - have strengthened cybersecurity
    - include commercial systems that augment government missions

- Capabilities that provide reliable access to space through:
    - the ability to frequently launch a range of payloads, from small and light to large and heavy
    - the ability to rapidly launch in the midst of a crisis, also known as tactically responsive space launch

- A strategy to deter attacks against U.S. and allied satellites via:
    - diplomatic or economic consequences in response to threatening behavior in space
    - the ability to hold adversarial satellites at risk

In the past, when ASATs were less threatening, satellite constellations usually consisted of a small number of relatively large, highly capable systems placed in the orbital region (LEO, MEO, GEO) best suited to the constellation’s mission.[54] These satellites had only a limited ability to change their orbital characteristics, rendering them relatively easy targets for ASATs.[55] Because of their small number, each satellite often represented a large percentage of a constellation’s total capability, thus increasing the potential disruption of a single ASAT attack.

A more resilient system would distribute critical communications, ISR, PNT, and missile warning capabilities across a larger number of satellites, as well as spread those satellites across multiple orbital regions.[56] Each individual satellite would provide a lower percentage of the constellation’s total capability, generally allowing it to be smaller and to cost and weigh less. Another tool to improve resiliency would be to design new satellites with increased maneuverability once in orbit, making it more difficult for adversaries to track and target them.[57] Additional measures that would significantly improve a constellation's defensibility and overall resilience would be leveraging commercial satellite systems to augment government mission capabilities, building in a degree of on-orbit redundancy, and shoring up cybersecurity.[58]

China and Russia have both demonstrated kinetic ASATs, but the weapons are expensive and challenging to mass-produce. Distributing capabilities across a larger number of dispersed, maneuverable satellites would make each spacecraft more difficult to hit, reduce the mission impact if an ASAT did hit its target, and ultimately raise the cost for an adversary to engage in space warfare. Non-kinetic ASATs may be less expensive to deploy, but they are still less effective against a larger number of satellites.

A resilient space architecture also depends on a robust space launch capacity. It is beneficial to maintain a number of launch pads and complexes to facilitate reliable access to space. Additionally, operating multiple launch vehicle models rather than relying on a single rocket design is preferable for several reasons.[59] First, should a launch vehicle fail to reach space, the resulting investigation would likely necessitate the temporary suspension of all launches of that particular rocket model. Should that investigation find a design flaw or manufacturing issue, launch vehicles would need to be fixed, limiting a country's launch capabilities. Second, models range in size and propellant type (solid or liquid fuel), which means the best launch vehicle can be selected for each unique satellite mission.[60] A robust launch ecosystem consisting of multiple vehicle versions operating from a wide range of locations provides the payload capacity and reliable access to space necessary to build a resilient space architecture.

Separate from reliable access to space, tactically responsive space launch (TRSL) is the ability to quickly replace satellites damaged or destroyed by an adversary, or by accident, and is a key component of a resilient space architecture.[61] Ideally, a responsive launch would occur just days after direction, which would require both the satellite and launch vehicle to be in storage and available in near ready-to-launch states. A responsive launch capability should be scalable, meaning it could replace a single satellite or an entire constellation. A country would benefit from being able to access multiple orbital regions (LEO, MEO, GEO, cislunar) through TRSL, though this may not be necessary. For example, it may be possible to replace a communications capability originally hosted by a satellite in GEO using multiple satellites in LEO, an orbital region much easier to access.[62] Finally, TRSL should itself be resilient, given that it would likely be needed in a high-end conflict scenario. Therefore, TRSL is more effective if launch vehicles are less dependent on sophisticated launch facilities, which are vulnerable to malfunctions as well as to both cyber and kinetic attacks. Currently, U.S. space launch predominantly depends on such launch facilities.[63]

The final piece examined for this study is maintaining a credible deterrent against attacks on satellite systems. Deterrence begins with denying an adversary the benefit of attacking by building satellites and launch vehicles that adhere to the previously described components of a resilient space architecture. Deterrence can also take the form of diplomatic or economic consequences in response to any activity that infringes on a nation's freedom to access or operate in space.[64] A formidable and scalable ASAT capability consisting of kinetic and non-kinetic options should, however, underpin a country's deterrence strategy. With the exception of India, the nations that have developed and tested kinetic ASATs have also built extensive space architectures that they leverage for both economic and military purposes.[65] The ability to hold an adversary's satellite systems at risk is a powerful deterrent, and one that makes robust ASAT capabilities an important component of space resilience.[66]

Indicators of China’s Progress toward Space Resilience

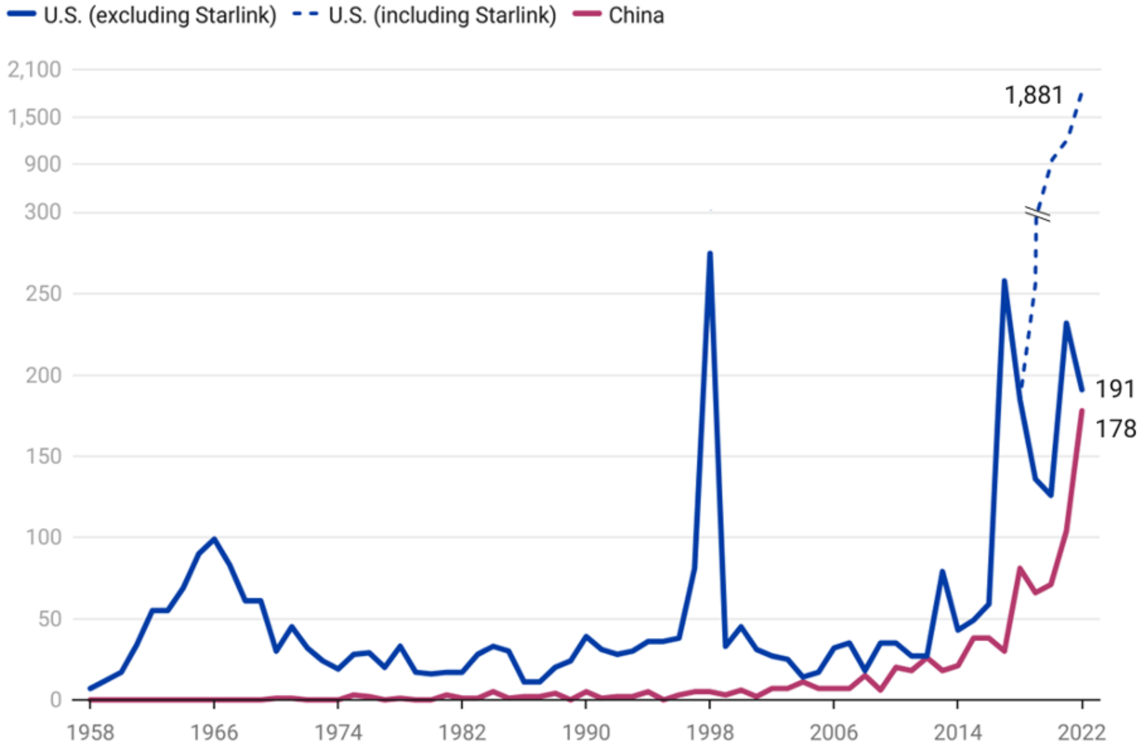
While it is difficult to comprehensively define space resilience, Washington and Beijing have both acknowledged the importance of creating resilient space architectures.[67] China has not, however, publicized its approach to improve space resilience, and we cannot assume it plans to do so in the same way as the United States. Though China’s overall space resilience objectives are unknown, it is possible to better understand China’s progress toward improving its space resilience by assessing its actions through the lens of what the United States considers critical in this area. This paper focuses on four of the 10 previously introduced resiliency components: disaggregation through proliferation of on-orbit capability, orbit diversification, general launch capacity, and TRSL. These components were selected because there is sufficient open-source data available to assess each one. A more in-depth assessment of space resilience would examine all components and consider the capabilities of individual satellites or constellations. However, given the lack of open-source information on specific Chinese satellite technologies, such an in-depth assessment is beyond the scope of this paper.

By consolidating publicly available information on orbital-class launch vehicles, space launch events, and the number and location of satellites placed in orbit from the start of China’s space program through the end of 2022, we are able to identify trends in China’s satellite and launch vehicle development that indicate progress toward increased space resilience. Any improvement in space resilience is noteworthy, as it results in a Chinese space architecture more resistant to disruption or degradation.

Proliferated On-Orbit Capability

Though not all satellites have equal capabilities, China has, during the past two decades, accelerated its pace of placing satellites in orbit (see Figure 2). According to CelesTrak, which maintains a satellite catalog that attempts to track all human-made objects in space, China placed 178 satellites in orbit in 2022, far exceeding its previous record of 104 launched the year before.[68] The United States, for reference, launched 1,881 satellites in 2022, but that number drops to 191 when excluding SpaceX’s privately funded and operated Starlink satellite system.[69]

Figure 2. U.S. and Chinese satellites placed in orbit each year.[*]



Source: The data in Figure 2 is consolidated from CelesTrak's satellite catalog.[70]

Though China nearly matched the United States' non-Starlink launch tempo in 2022, no attempt is made in this study to compare the countries' respective space-based capabilities. Satellites of all sizes and functions are counted equally in Figure 2. That said, in the past decade (2013–22), China placed 645 satellites in orbit, compared with the United States' nearly 5,000.[71] Excluding Starlink, the U.S. figure is 1,358 satellites, more than double that of China.[72] Though China has placed fewer satellites in orbit than the United States, it is useful to reiterate that China now operates advanced PNT, ISR, and communications satellites, as well as experimental systems intended to test capabilities that could be used to attack other spacecraft.[73]

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[*] From 2019 through 2022, SpaceX launched more than 3,600 Starlink satellites, exceeding the total number of U.S. satellites launched in the history of U.S. spaceflight, according to CelesTrak.

Diversified Orbital Regions

China continues to place the majority of its satellites in LEO, partly because this region is more easily accessible but also because it is an ideal location for Earth-imaging satellites, as well as useful for many other missions including signal collection, communications, environmental monitoring, and manned spaceflight.[74] That said, LEO satellites are also the easiest to track and target using ASATs. For that and other mission-driven reasons, Beijing is increasing its satellite presence in the MEO, GEO, and cislunar regions.[75]

In 2018, China prepositioned in cislunar orbit the Queqiao relay (communications) satellite (鹊桥号中继卫星) in advance of the launch of its Chang'e 4 (嫦娥四号) spacecraft to the far side of the Moon.[76] The Queqiao's positioning enabled relay communications between the Chang'e 4 spacecraft and its ground station.[77] Though the Queqiao is performing an important mission for China's lunar program, it is the first communications satellite placed in orbit beyond the Moon, and at an altitude twelve times higher than GEO.[78] The Queqiao has provided China with valuable data on how to operate a communications satellite in the cislunar region of space, an area much less threatened by ASAT weapons.[79]

In 2021, China launched the Shiyan (实验) 10-01 experimental satellite into a Molniya orbit in what appears to be China's first-ever use of this orbit type.[80] With a highly elliptical, or oval-shaped trajectory, a Molniya orbit offers extended coverage over Earth's North Pole, enabling communications or Earth-sensing capabilities over a geographic area difficult to cover using more traditional orbits such as LEO, MEO, and GEO.[81] Given the Molniya orbit's highly elliptical shape, satellites in this region are sometimes as close to Earth as LEO satellites, and sometimes as far as or farther away than GEO satellites. Though likely not out of range of some ASAT systems, satellites in Molniya orbits are more difficult to intercept than those in LEO. So far, there have been no destructive ASAT tests in this orbital region.[82] In its final launch of 2022, China placed a second satellite, Shiyan 10-02, into a Molniya orbit, demonstrating a continued effort to expand into this region of space.[83]

The Queqiao and Shiyan 10 satellites are just a few examples of spacecraft placed in unique orbits that, when considered along with Beijing's growing satellite presence in MEO and GEO, indicate progress toward a more resilient space architecture through the diversification of satellite orbital regions.

Of China's 645 satellites launched in the past decade (2013–22), 551 were placed in LEO, 27 in MEO, and 57 in GEO, with eight in other orbits, including the Queqiao satellite in cislunar space and the two Shiyan 10 satellites in Molniya orbits.[84] For reference, over the same timeframe, the United States placed 1,249 of its 1,358 non-Starlink satellites in LEO, 21 in MEO, and 65 in GEO, with 23 placed in more unique orbits.[85] All of SpaceX's more than 3,600 Starlink satellites are in LEO.[86]

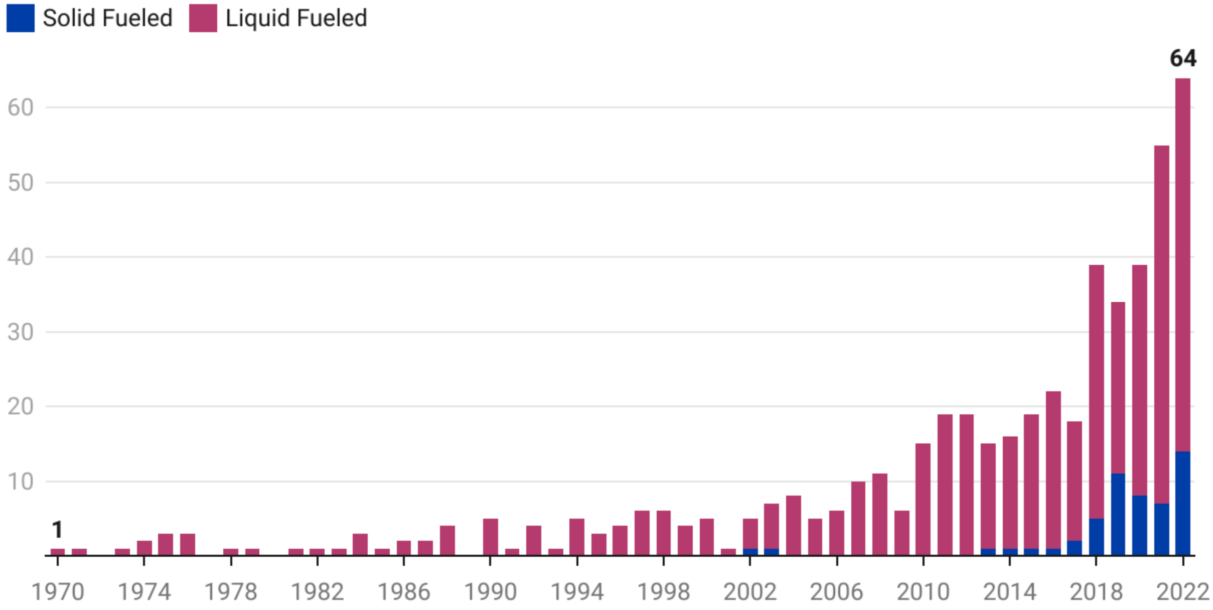
Increased Access to Space

China has significantly increased its space launch frequency since the turn of the century (see Figure 4). In 2022, Beijing managed 64 orbital-class space launches, or roughly one every six days, and has achieved this quick pace by expanding its rocket fleet and improving its launch infrastructure. China has added new pads to each of its three inland launch complexes, constructed a fourth complex on Hainan Island in the South China Sea, and built sea platforms that support space launch.[87]

Figure 3. Left: Long March-5B rolling to the launch pad at China's new Wenchang Space Launch Site on Hainan Island. Right: Long March-11H launching from a sea platform.

Sources: Wenchang Space Launch Site image from SpaceNews.[88] Sea platform image from NASA Spaceflight.[89]

Figure 4. China's orbital-class space launches per year.

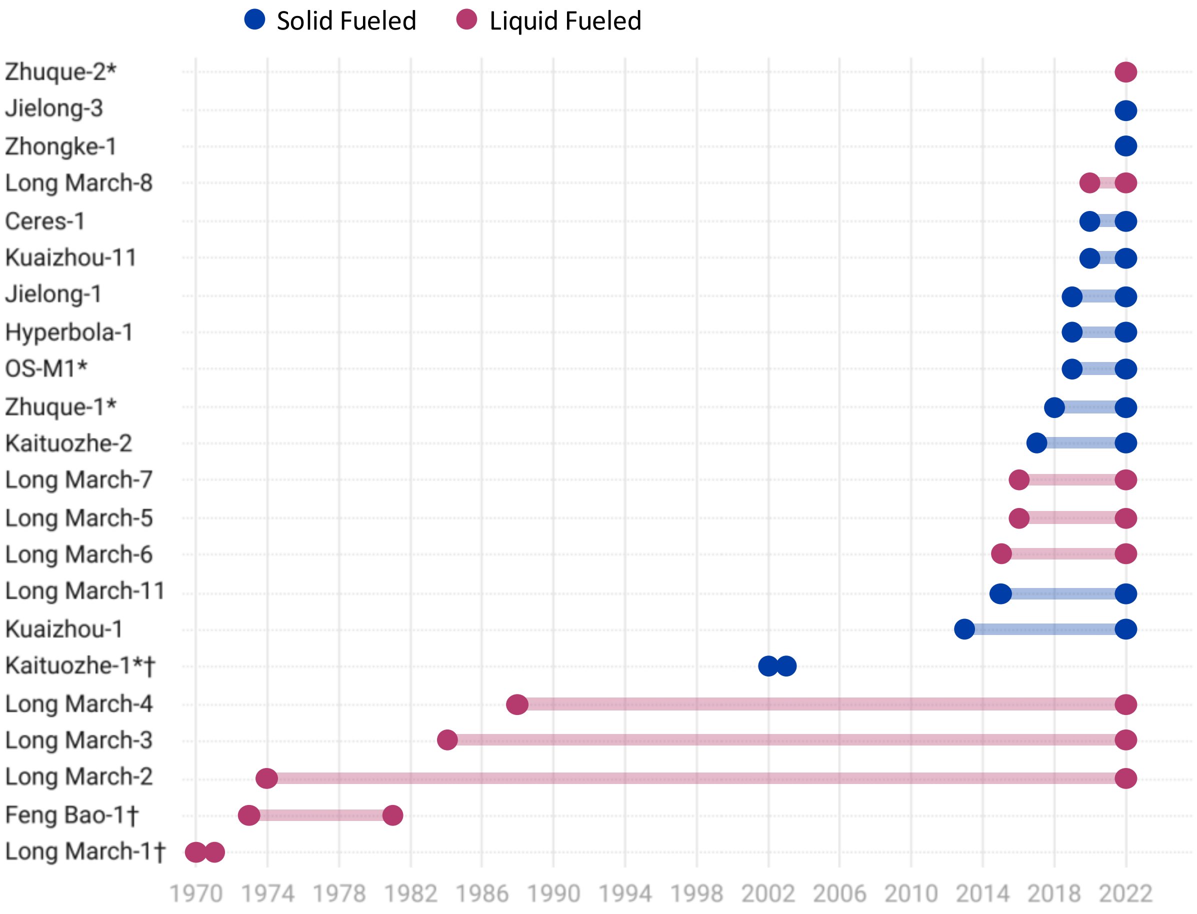


Source: The data in Figure 4 is consolidated from the United Nations Office for Outer Space Affairs (UNOOSA), Gunter's Space Page, and other sources included in "China-Space-Resilience," Georgetown-CSET.[90]

Traditionally, China has depended on three liquid-fuel launch vehicles, the Long March (长征系列运载火箭) -2, -3 and -4, as well as their respective variants. China has continued to operate these proven launchers while also developing five additional liquid-fuel rockets and eleven solid-fuel rockets in the past 10 years. Several of these new launch vehicles include multiple variants as well. Figure 5 depicts China's rapidly expanding launch vehicle fleet.

Beijing's new launch vehicles offer a range of payload capacities, from the smaller, solid-fuel Long March-11 to the heavy-lift, liquid-fuel Long March-5, providing China with the flexibility to select the best rocket for each mission.[91] Beijing's new liquid-fuel launch vehicles also use more efficient, less toxic propellants than their older Long March counterparts.[92] One of these, the Zhuque-2 (朱雀二号) is designed to burn liquid methane and liquid oxygen, a challenging combination of fuel and oxidizer due to their similar boiling points.[93] Despite this challenge, methane is a cost-efficient, clean burning, energy-dense fuel that is ideal for reusable rockets.[94] In its first launch attempt, the Zhuque-2 lifted off from China's Jiuquan Satellite Launch Center (酒泉卫星发射中心) on December 14, 2022.[95] After what appeared to be a normal performance of the rocket's first stage, an anomaly occurred during the second stage burn, and the rocket failed to reach orbit.[96] Had the Zhuque-2 succeeded in reaching orbit, it would have been the world's first methane-fueled launch vehicle to do so, ahead of several U.S. methane-fueled rockets including SpaceX's Starship and United Launch Alliance's Vulcan.[97]

Figure 5. China's orbital-class launch vehicles, categorized by years of operation and fuel type. Several of these include multiple variants that are not delineated in this figure.



* The Zhuque-1, OS-M1, and Zhuque-2 have each attempted one launch and failed to achieve orbit. The Kaituozhe-1 (开拓者一号) failed to achieve orbit in its two launch attempts.

† Due to prolonged inactivity, we have listed the Long March-1, Feng Bao-1, and Kaituozhe-1 as no longer in operation. The year of their last orbital launch attempt is depicted in the figure.

Source: The data in Figure 5 is consolidated from UNOOSA, Gunter's Space Page, and other sources included in "China-Space-Resilience," Georgetown-CSET.[98]

China has also used its new solid-fuel rocket fleet to support its expansion into launches from sea. Sea launch platforms enable additional launch capacity with the added benefit of being able to change their position, allowing easier access to all regions of space.[99] Through 2022, China has performed five sea-platform launches, all successful, using the Long March-11H and the Jielong-3 (捷龙三号运载火箭).[100]

During the past ten years (2013–22), Beijing performed 322 orbital-class launches, with 64 in 2022.[101] Washington, for reference, launched 358 orbital-class rockets in the same timeframe, including 87 in 2022.[102] Regarding launch reliability, China's Long March rocket family, which forms the foundation of its space launch industry, has achieved orbit in 278 of 284 attempts over the past decade, with six failures occurring during Long March-3, -4, -5, and -7 launches.[103] By comparison, among the United States' most depended-upon rockets, the Atlas V and Delta IV, have never failed to reach orbit in their 20-year histories, and the Falcon 9 has suffered only two failures—one during flight and one on the launch pad—since its first launch in 2010.[104] From 2013 through 2022, these three U.S. rockets have accounted for 277 successful launches in 279 attempts.[105]

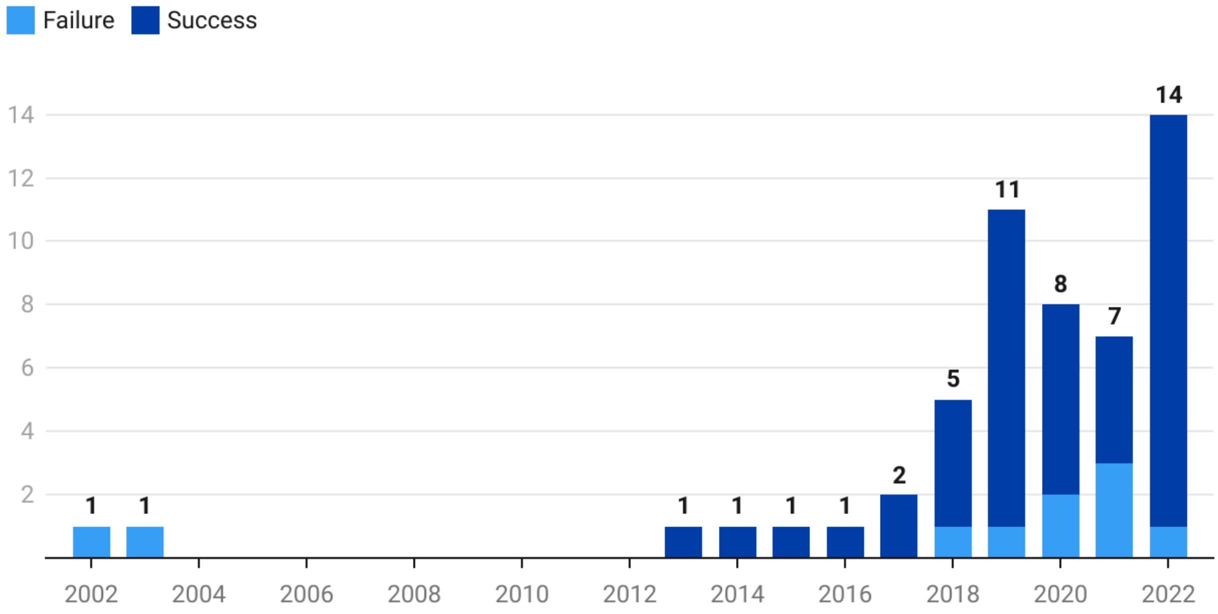
China's Approach to Tactically Responsive Space Launch

As China has improved its overall space resilience—at least according to the indicators discussed here—it has also bolstered its TRSL capability. In this section, we assess China's TRSL capability based on publicly available information about its launch events and launch vehicles. Due to a lack of available information on China's hardware production timelines, we cannot determine how long China requires to build its satellites and launch vehicles. If, however, they are built in advance of need and stored in near ready-to-launch states, several of China's newly developed launch vehicles are ideally suited to enable TRSL. Moreover, Beijing appears to have demonstrated a TRSL capability more mature than that of Washington, at least when viewed through the approach of using mobile, solid-fuel rockets to achieve rapid responsive launch (alternative approaches are discussed in a later section).

China's TRSL capability depends on its new fleet of solid-fuel launch vehicles. While liquid-fuel launch vehicles are generally more fuel efficient, they are often more difficult to launch, usually requiring extensive ground support equipment integrated into a carefully engineered launch pad.[106] Solid-fuel rockets, on the other hand, are less efficient but relatively easier to launch, and they can be designed to require minimal ground support equipment.[107] Furthermore, if these launch vehicles are small enough, they can be designed for quick transport and launch from specialized trucks known as TELs (transporter erector launchers), which require little-to-no ground support equipment.[108] Over the past decade, China has improved its solid-fuel launch capabilities and designed several of its new solid-fuel launch vehicles to be TEL-compatible.[109]

Given the suitability of solid-fuel rockets for TRSL, we gathered open-source information about China's solid-fuel rocket launches. Figure 6 shows that Beijing has attempted 53 orbital-class, solid-fuel launches from its first-ever solid-fuel launch attempt in 2002 through 2022, with a notable increase after 2017. Fourteen of the 53 launches occurred in 2022 alone. While 10 of the 53 failed to reach orbit, half of these failures occurred during the initial tests of new rocket models, which may indicate the prioritization of speedy solid-fuel launch vehicle development while accepting increased risk of launch failure.[110]

Figure 6. China's orbital-class, solid-fuel launches per year from 2002 through 2022, categorized by success or failure.



Source: The data in Figure 6 is consolidated from UNOOSA, Gunter's Space Page, and other sources included in "China-Space-Resilience," Georgetown-CSET.[111]

In its efforts to quickly grow its solid-fuel launch capabilities, Beijing has leaned on both its traditional launch vehicle developers and newly established space companies. While most of its solid-fuel rockets come from the state-owned China Aerospace Science and Technology Corporation (CASC, 中国航天科技集团有限公司) and China Aerospace Science and Industry Corporation (CASIC, 中国航天科工集团有限公司), at least five launch vehicles were designed by recent entrants into the Chinese space launch industry (see Table 1). These newer companies remain in their infancy, however, as evidenced by the relatively small number of their launches (11 new entrant launches of 53 total solid-fuel launches), and their relatively high failure rate (five launch failures out of 11 new entrant launches).

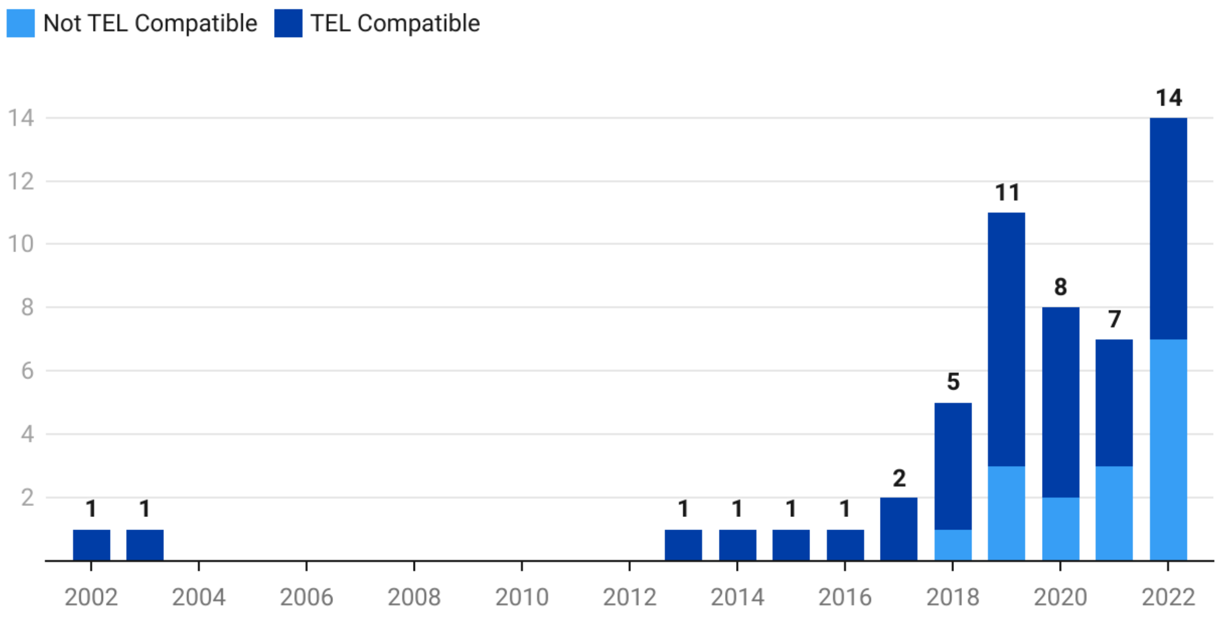
Table 1. China’s 14 orbital-class, solid-fuel launch vehicle variants from 2002 through 2022, categorized by developer.

CASC, CASIC, and Subsidiaries					**Non-CASC/CASIC**				
Launch Vehicle Name	**Developer**	**Platform**	**Launches**		**Launch Vehicle Name**	**Developer**	**Platform**	**Launches**	
			Success	**Failure**				**Success**	**Failure**
Kaituozhe-1	CASIC	TEL Compatible	0	2	Zhuque-1	LandSpace	Not TEL Compatible	0	1
Kaituozhe-2	CASIC	TEL Compatible	1	0	OS-M1	OneSpace	Not TEL Compatible	0	1
Kuaizhou-1	ExPace (CASIC Sub)	TEL Compatible	2	0	Hyperbola-1	iSpace	Not TEL Compatible	1	3
Kuaizhou-1A	ExPace (CASIC Sub)	TEL Compatible	16	2	Ceres-1	Galactic Energy	Not TEL Compatible	4	0
Kuaizhou-11	ExPace (CASIC Sub)	TEL Compatible	1	1	Zhongke-1	CAS Space	Not TEL Compatible	1	0
Long March-11	CALT (CASC Sub)	TEL Compatible	11	0					
Long March-11H	CALT (CASC Sub)	Not TEL Compatible	4	0					
Jielong-1	CALT (CASC Sub)	TEL Compatible	1	0					
Jielong-3	CALT (CASC Sub)	Not TEL Compatible	1	0					
TOTAL			**37**	**5**	**TOTAL**			**6**	**5**
			Success	**Failure**				**Success**	**Failure**

Source: The data in Table 1 is consolidated from UNOOSA, Gunter’s Space Page, and other sources included in “China-Space-Resilience,” Georgetown-CSET.[112]

As mentioned previously, smaller rockets designed for launch from TELs provide added mobility relative to their larger counterparts and, when solid-fueled, offer the ability to launch from less resource-intensive facilities or possibly just flat pads. Both characteristics are advantageous for TRSL. These benefits are not without costs, however, as launch vehicles small enough to operate from TELs have less payload capacity than larger rockets that require fixed launch installations, regardless of fuel type. Given the benefit of mobility in support of TRSL, we analyzed the same 53 solid-fuel launches by launch vehicle model and whether that model is capable of being launched via TEL. As Figure 7 shows, 37 of the 53 launches, or nearly 70 percent, used TEL-compatible rockets. Additionally, all TEL-compatible rockets were designed by Beijing’s traditional space industrial base: CASC, CASIC, and their subsidiaries.

Figure 7. China’s orbital-class, solid-fuel launches from 2002 through 2022, categorized by TEL compatibility.



Source: The data in Figure 7 is consolidated from UNOOSA, Gunter’s Space Page, and other sources included in “China-Space-Resilience,” Georgetown-CSET.[113]

Across the 53 orbital-class, solid-fuel launches, China’s workhorses have been the TEL-compatible Kuaizhou-1A (快舟一号甲) and Long March-11. Due to their smaller size, the Kuaizhou-1A and Long March-11 are likely able to access only LEO. That said, a TRSL capability should be able to access all inclinations of LEO where satellites may need to be replaced, whether near the Earth’s equator, the North or South Poles, or anywhere in between. A launch facility’s latitude and local geography determine which orbital inclinations it can efficiently access.[114] China has operated the Kuaizhou-1A from all three of its mainland launch centers and the Long March-11 from Jiuquan, in Inner Mongolia, and from the Xichang Satellite Launch Center (西昌卫星发射中心), in Sichuan Province, demonstrating both a degree of geographic redundancy and the ability to access all important LEO inclinations.[115] Furthermore, because both rockets are TEL-compatible, China is likely able to transport and launch these rockets from locations that are not in the immediate vicinity of its established launch centers. Beijing has also described both launch vehicles as capable of launching on short notice after being kept in storage, which would render these particular models critical for buttressing China’s TRSL capability.[116]

Figure 8. Left: Kuaizhou-1A. Right: Long March-11.

Sources: Kuaizhou-1A image from Sina News.[117] Long March-11 image from GlobalSecurity.org.[118]

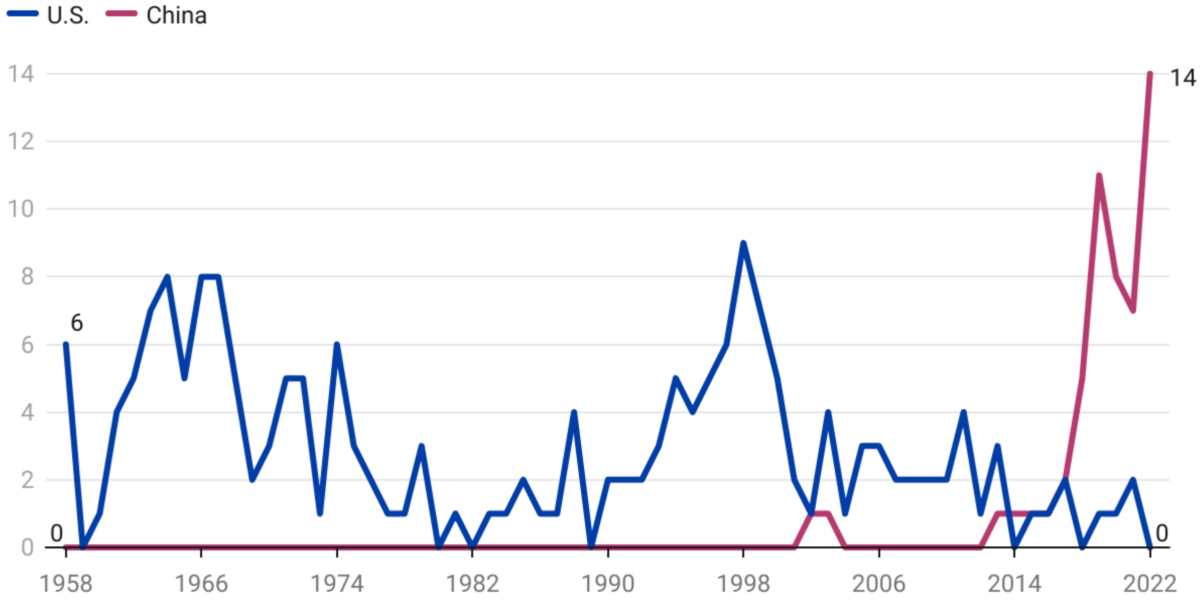
As already noted, TEL-compatible rockets are smaller and have less payload capacity. An effective TRSL capability should have enough payload capacity to quickly replace multiple satellites if needed. To account for the limitation of smaller payload capacity, China need simply demonstrate the ability to launch its TEL-compatible rockets from disparate launchers in quick succession—something it successfully accomplished on December 7, 2019, when two Kuaizhou-1A launch vehicles lifted off from different TELs at Taiyuan Satellite Launch Center (太原卫星发射中心) in Shanxi Province, just six hours apart, placing seven satellites in orbit.[119]

Beijing's effort to build and test multiple TEL-compatible, solid-fuel rockets is a strong indication of its desire to field an operational TRSL capability.[120] Moreover, Beijing's apparent progress toward a TRSL capability exceeds that of the United States, at least when viewed through the approach of using mobile, solid-fuel rockets to achieve rapid responsive launch.

U.S. Efforts to Develop Tactically Responsive Space Launch

Unlike China, the United States developed solid-fuel launch vehicles in parallel with its first liquid-fuel rockets. In February 1961, three years after its first successful satellite launch, the United States launched the Explorer 9 satellite using the Scout X, a four-stage solid-fuel rocket.[121] Despite the United States' long history with solid-fuel rockets and their regular use as strap-on boosters for liquid-fuel launch vehicles, U.S. solid-fuel rocket capabilities have dwindled in recent years. Figure 9 shows all orbital-class, solid-fuel launches carried out by the United States and China. In the past 10 years, the United States has launched only 11 orbital-class, solid-fuel rockets, while China has launched 51.

Figure 9. All U.S. and Chinese orbital-class, solid-fuel launches per year.



Source: The data in Figure 9 is consolidated from UNOOSA, Gunter's Space Page, and other sources included in "China-Space-Resilience," Georgetown-CSET.[122]

The United States, for its part, has prioritized payload capacity, fuel efficiency, and reliability within its launch vehicle fleet, resulting in the large liquid-fuel rockets that have positioned the nation as a global leader in reliable access to space. Washington, however, has not prioritized mobility or speed of launch, and it currently operates only the Pegasus XL and the Minotaur family of orbital-class, solid-fuel launch vehicles, both produced by Northrop Grumman.[123] The Pegasus XL was designed in the late 1980s and early 1990s, and the Minotaur launch vehicle family relies on decommissioned ICBM engines produced more than 30 years ago.[124] Minotaur launch vehicles require fixed launch platforms, though the Pegasus XL deploys from an aircraft, thus enabling mobility comparable to China's TEL-compatible launch vehicles. It does, however, have a similar payload capacity limitation.[125]

U.S. efforts to develop responsive launch began as early as 2007, with the establishment of the Joint Operationally Responsive Space Office, tasked by the Department of Defense with providing quickly deployable space capabilities to meet warfighter needs.[126] Since its inception, however, the ORS Office has struggled to drive change within the existing space acquisition community.[127] Renewing the call for TRSL, leaders from the USSF, Department of the Air Force, USSPACECOM, and Congress have recently reiterated that the United States needs the ability to quickly reconstitute on-orbit capability through responsive launch.[128] But as of 2023, the U.S. government has provided relatively limited funding for TRSL: $15 million in 2021, $50 million in 2022, and $50 million in 2023.[129]

Despite a relatively small budget, the USSF has made progress toward achieving some TRSL capability, as evidenced by the June 2021 launch of the aforementioned Northrop Grumman Pegasus XL, which carried a military satellite to LEO.[130] The solid-fuel Pegasus XL successfully achieved orbit only 21 days after being directed to launch, and less than one year after then–USSF Chief of Space Operations General John Raymond challenged his service to demonstrate a TRSL capability.[131]

The USSF is also planning a second responsive space launch test in 2023, with Firefly Aerospace's Alpha launch vehicle, a liquid-fuel rocket.[132] During the upcoming test, the USSF will attempt to launch the Alpha from a fixed launch pad within 24 hours of direction, which would be, if successful, a promising step toward TRSL.[133]

Relative to solid-fuel launch vehicles optimized for mobility and rapid launch, such as the previously discussed Chinese Kuaizhou-1A and Long March-11, liquid-fuel rockets, especially those using cryogenic (very low temperature) propellants, require the synchronized operation of complex ground support equipment to complete a number of pre-launch activities such as fueling the launch vehicle and preparing its engines for ignition, any of which could malfunction and threaten a speedy launch.[134] This drawback, however, is balanced by the opportunity to use larger launch vehicles with greater payload capacity than their more mobile, but smaller counterparts.

During the Space Force's first responsive launch test in 2021, General Raymond lauded the USSF and its partners' ability to prepare both the satellite and the launch vehicle in less than a year, a respectable accomplishment given that the process often takes two to five years.[135] But even if the upcoming responsive space launch test is a success, the United States' two TRSL demonstrations would be on par with the capability demonstrated by China a decade ago during its first successful TEL-compatible, orbital-class launch.[136] Furthermore, China has continued to prioritize the development of TEL-compatible, solid-fuel launch vehicles, and by extension its apparent TRSL capability, leaving a gap on which the United States would need to focus resources in order to close.

How the United States Might Close the Responsive Launch Gap with China

TRSL is an important component of a resilient space architecture. It is, however, just one component, and developing a reliable TRSL capability will be costly and time-consuming. The U.S. government has multiple options to ensure resilience in space. As noted in this paper's discussion of the various components of resilient space architectures, the United States should continue to disaggregate satellite constellations, diversify orbital regions, and/or leverage commercial systems, among other options. It is also worth considering alternatives to satellites, such as unmanned air, sea, and ground vehicle relays and sensors.[*] Each of these options has its own limitations, but also provides immediate benefits and can reduce the impact of lost satellites and, therefore, the ultimate need for a TRSL capability to replace those satellites.

These alternatives aside, and focusing specifically on addressing TRSL capacity and capability, U.S. policymakers should consider the following actions:

1. **Develop strategies for managing stored inventories of satellites and technical designs consistent with TRSL objectives.**
   Tactically responsive space launch depends, above all, on maintaining satellites and rockets in near ready-to-launch states so that they can be launched quickly once needed. The U.S. government should consider developing the satellite acquisition strategies necessary to produce and manage stored satellite inventories in parallel with satellites built to meet current on-orbit requirements. Additionally, the government should prioritize satellite designs that enable removal from storage and launch on short notice, as well as compatibility with multiple launch vehicles. Such satellites would minimize the time required to reestablish a degraded on-orbit capability, while also protecting against the potential disruption of a launch vehicle failure. Carefully crafted strategies allowing for satellites to be rotated in and out of storage could minimize deterioration and enable technology insertion among stored satellite inventories.

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[*] China has demonstrated an interest in this approach, as evidenced by its deployment of high-altitude ISR balloons over the United States and other areas. Though the aircraft appear to be relatively low-tech, China is gaining experience in their use, as well as intelligence on how the United States and other nations detect and respond to them. See Kevin Pollpeter, "How China Might Use High-Altitude Balloons in Wartime" (Center for Naval Analysis, February 22, 2023), https://www.cna.org/our-media/indepth/2023/02/how-china-might-use-high-altitude-balloons-in-wartime.

2. **Increase investments in solid-fuel launch vehicles.**
   China has utilized small, mobile, solid-fuel rockets to improve its TRSL capabilities, and the United States has, so far, demonstrated a similar approach with its inaugural TRSL test using the air-launched, solid-fuel Pegasus XL in 2021.[137] As previously noted, however, the U.S. fleet of orbital-class, solid-fuel launch vehicles is flight-proven but uses aging technology.[138] New solid-fuel rockets can be designed for easy transport, less dependence on ground support infrastructure, and the ability to be stored for long periods and launched quickly. Should the U.S. government pursue such launch vehicles to boost its TRSL capabilities, it would require new investments in solid-fuel launch vehicle technology with a focus on storability, mobility, minimizing required ground support equipment, and rapid launch capability.[*]

3. **Partner with commercial launch providers to develop and maintain liquid-fuel launch vehicles for TRSL.**
   To meet its TRSL objectives, the U.S. government could partner with the American commercial launch industry to bolster the capabilities of one or more existing liquid-fuel launch vehicles. Though most commercial, liquid-fuel rockets are not designed to launch on short notice, commercial and government interests in reducing launch preparation timelines may be aligned, and the commercial space industry is already exploring how to quicken its launch pace. SpaceX, for example, launched and landed a reusable, liquid-fuel Falcon 9 booster on April 8, 2022. The company then refurbished the booster, integrated a second stage and payload, and launched the rocket again three weeks later, on April 29.[139] If the U.S. government partnered with SpaceX to ensure that one or more Falcon 9 boosters were kept in a ready-to-launch state, a responsive launch could be possible within a similar timeline. Relative to small, mobile, solid-fuel rockets,

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[*] The U.S. military has partnered with the commercial space industry to develop the LGM-35A Sentinel, a three-stage, solid-fuel ICBM intended to modernize the ground-based leg of the U.S. nuclear triad. The military and commercial space industries have worked together in the past to convert decommissioned solid-fuel ICBMs into the Minotaur family of orbital-class launch vehicles. They could follow a similar model, taking advantage of solid-fuel technology designed for Sentinel to streamline the development of an orbital-class, solid-fuel rocket ideal for TRSL. See “Minotaur,” Northrop Grumman, accessed March 16, 2023, https://www.northropgrumman.com/space/minotaur-rocket/; and “LGM-35A Sentinel Intercontinental Ballistic Missile, USA,” *Airforce Technology*, July 29, 2022, https://www.airforce-technology.com/projects/lgm-35a-sentinel-intercontinental-ballistic-missile-usa.

liquid-fuel launch vehicles operating from fixed installations carry the added risk of requiring complex ground support infrastructure that is vulnerable to malfunction or cyber/kinetic attack. The increased payload capacity, however, along with the ability to use existing commercial launch vehicles, are beneficial enough factors to consider a commercial launch provider partnership as a viable TRSL option.

Increased resilience across the U.S. space architecture results from the combined effect of strengthening each of the components previously described: disaggregated and distributed satellite constellations, reliable and responsive access to space, and a credible deterrent against attack. The U.S. government must choose how to balance investments in these components given a limited set of resources. That said, TRSL protects against a worst-case scenario in which critical space-based capabilities are lost, likely as a result of a conflict. In such a crisis, every minute required to reestablish that capability matters.

Conclusion

This paper uses open sources to outline China’s progress toward improving the resiliency of its space architecture. We argue that Beijing has increased its space architecture resilience through proliferating on-orbit capability, diversifying satellite orbital positions, and expanding access to space.

The most important finding, however, is that China appears to hold an advantage over the United States in the low-likelihood, high-consequence scenario where crucial mission-supporting satellites need to be quickly replaced. The United States maintains the most advanced space industry in the world, but it has not demonstrated a commensurate ability to launch rockets on short notice. Washington cannot assume that its space industry will be capable of pivoting to an acceptably fast launch tempo if the need to do so arises.

If the U.S. government wants to close the TRSL gap with China, or at least prevent it from growing further, it should consider how to develop TRSL capabilities sooner rather than later. To that end, we have laid out several potential approaches to quicken the tempo of U.S. space launch. These include building and storing satellites designed for rapid launch; boosting investment in mobile, solid-fuel launch vehicles (China’s current approach); and partnering with commercial launch providers to develop and maintain liquid-fuel launch vehicles capable of TRSL.

Authors

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Disclaimer

The conclusions and opinions expressed in this research paper are those of the authors and do not necessarily reflect the official policy or position of the U.S. government, the U.S. Department of Defense, the U.S. Space Force, or Air University. Any and all errors are those of the authors alone.

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Endnotes

[1] U.S. space policy makes clear the need to protect and defend U.S. and allied interests in space; see The National Space Policy, 85 Federal Register 81755 (Dec. 16, 2020), 81770-1, https://www.federalregister.gov/documents/2020/12/16/2020-27892/the-national-space-policy. China's space policy is less explicit, although its desire for improved space resilience is evident through its activities, summarized in this paper, which include the development and 2007 testing of a kinetic anti-satellite weapon. See William J. Broad and David E. Sanger, "China Tests Anti-satellite Weapon, Unnerving U.S.," *The New York Times*, January 18, 2007, https://www.nytimes.com/2007/01/18/world/asia/18cnd-china.html.

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[5] The United Nations Office for Outer Space Affairs (UNOOSA) and Gunter's Space Page maintain databases of space launch events. These databases often include the launch vehicle, complex, and pad used as well as whether the launch was a success or a failure. We cross-referenced these databases with other sources that provide launch vehicle specifics such as developer, fuel type, TEL-compatibility (for Chinese launch vehicles), and air- or-ground launch compatible (for U.S.-launched vehicles). For more on UNOOSA's database, see "Online Index of Objects Launched into Outer Space," United Nations Office for Outer Space Affairs, accessed March 16, 2023, https://www.unoosa.org/oosa/osoindex/. See also Gunter D. Krebs, "Launch Vehicles," Gunter's Space Page, accessed March 16, 2023, https://space.skyrocket.de/directories/launcher.htm. The cross-referenced data used for this study, which includes all other sources, can be found at "China-Space-Resilience," Georgetown-CSET.

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