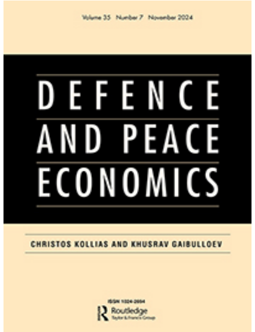

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Star Wars: Anti-Satellite Weapons and Orbital Debris

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ABSTRACT
The militarization and weaponization of outer space are increasing continuously with the development of new and more advanced space weapon systems by a growing number of nations. This is a direct consequence of the high and growing strategic value of outer space for defense, security, and warfare. This paper reviews trends in space weapon systems and analyzes the implications of anti-satellite military weapons for human activities in outer space. A direct consequence of the completion of anti-satellite military tests is that the amount of orbital debris has increased significantly. We use a simple physical – economic model to illustrate how anti-satellite military tests, particularly those using direct-ascent weapons, dramatically increase the probability that the Kessler syndrome will occur. Whereas the long-run impact of low altitude anti-satellite tests is limited because of atmospheric drag, at high altitude direct-ascent anti-satellite tests are persistently harmful for human activities in space. The paper also provides a simulation of the long-run effects of a war in space.

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Introduction

On 15 November 2021, a Russian PL-19 Nudol missile destroyed a defunct military Soviet satellite (Cosmos-1408) in a direct-ascent anti-satellite (DA-ASAT) test. The target, weighing around 1,750 kg, was intercepted at an altitude of 485 km, in an orbit that is densely populated by satellites and other spacecraft. According to the US Space Command (USSC), a cloud of more than 1,500 pieces of debris trackable by ground-based radar (items larger than 10 cm) was generated by the impact, and it is estimated that hundreds of thousands of smaller fragments were also produced. The cloud of debris from the impact spread over an altitude range from 300 to 1,100 km (NASA 2022), increasing the risk of collision with spacecraft in a big region of the low Earth orbit (LEO).[1] The International Space Station (ISS), at an orbit altitude of 408 km, was alerted to the risk of collision with the cloud of debris generated by the test, and the Chinese Space Station was also put in jeopardy. The seven astronauts on board the ISS, including two Russian crew members, undertook emergency procedures for their safety and took shelter in the escape capsules.

We begin this paper with the description of that particular event to highlight one of the most direct implications of the militarization and weaponization of outer space for present and future human activities in space; the deliberate creation of more orbital debris. Military, and also civil,[2] satellites offer a number of strategic advantages for security, national defense, and warfare, and thus the military use of outer space started at the very beginning of the space exploration era. The use of space for defense purposes significantly enhances the military capacity of spacefaring nations, and has also generated positive effects on arms ban treaties by increasing verification and monitoring. On the other hand, military communications, weather forecasting for military activities, geographic positioning of combat units, control and guidance of intelligent weapon systems, surveillance, reconnaissance and

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intelligence information, and so on are vital for modern defense and warfare, driving weaponry technology, tactics, and doctrine for the main military powers. Indeed, the first stage of launch systems has been developed from ballistic missile technology, and the initial exploration of outer space was firmly based on military objectives. Apart from the military origin of launch systems, the interest of outer space for defense has been increasing, given the ever-growing possibilities offered by space for military activities. All these elements explain the increasing militarization of outer space.

However, the militarization of outer space does not only include passive non-armed military equipment in orbit. A number of spacefaring nations have developed a variety of anti-satellite (ASAT) weapon systems, both Earth-based and space-based, leading to an increasing weaponization of outer space.[3] Bernat (2019) remarked on the increasing strategic importance of satellites and other orbital systems, including orbital weapon systems, which has led the main spacefaring countries to develop new space weapon systems and to create specific units for space warfare. Importantly, the traditional distinction between militarization and weaponization vanishes in outer space, where almost every object with maneuverability capacity can be used as a weapon because of the high velocities (White 2017), civil satellites and spacecraft can also be used for military purposes, and, in general, any technology has a dual use. The disappearance of the distinction between militarization and weaponization has harmful effects on the rest of human activities, commercial and scientific, in outer space, even in peaceful times, and could be a serious obstacle to the development of future in-space industries. Whereas it can be argued that the militarization of outer space does not have harmful effects per se, except that more spacecraft are inserted into orbit, further congesting the near-Earth orbit, the importance of these assets for national defense and warfare makes them targets for potential foes. Infant industries that are expected to develop in the near future, such as space-based industries for servicing, refueling, upgrading, maintenance and repairs, can be hindered by military considerations, as all these technologies are dual-use and can be used as weapons. Furthermore, any active debris removal policy will be put at risk given its potential use as an offensive weapon.

On the other hand, the militarization and weaponization of outer space are closely related to the population dynamics of orbital debris, which has a negative impact on commercial and other human activities in the Earth's orbit. Weinzierl (2018) reviews the key characteristics of the space economy, including the economic implications of overuse, congestion and orbital debris. Phillips and Pohl (2021) studied the issue of orbital debris from a behavioral economic perspective, focusing on the relationship with national defense. They argued that orbital debris represents a threat to the national security interests of spacefaring nations.

The relationship between ASAT tests and orbital debris is twofold. First, direct-ascent (DA) ASAT tests that consist of the destruction of a target satellite or the self-destruction of the weapon produce a considerable amount of new orbital debris. Second, the development of debris removal vehicles is suspicious, as they have a double use and can also be considered as ASAT weapons, being an obstacle to the implementation of active mitigation policies for reducing orbital pollution (Dobos and Prazak 2019). Indeed, any technology for active debris removal could also be considered as a weapon, as this technology has the ability to remove any object, including enemy satellites, from orbit.[4]

Unfortunately, the problems of the weaponization of space do not finish here.[5] Military satellites are vital for military capacity, and hence satellites are principal potential targets in case of conflict among the major powers. A country's own military satellites will also be targets for the enemy if there is a conflict between spacefaring nations with ASAT capabilities. In this environment, a war in space would have dramatic consequences for human access to and use of the near-Earth orbit, with the creation of enormous clouds of debris from the destruction of satellites. High value services from satellites would be interrupted, with a harmful effect on normal life. From a military perspective, the operational capacity of forces would be greatly affected. Without long-range communication, reconnaissance and GPS for drones and guided bombs, and even weather information, the operational capacity of modern forces would be significantly reduced. Not only would enemy target satellites be destroyed in a hypothetical war, but the resulting large amount of debris would be an additional threat for any surviving satellite and any other human activity in space. Therefore, there is a direct link between the strategic value of space for military and defence activities and the rest of commercial and scientific activities, even in peace times, as weaponization of the space is an important source of orbital debris production.

This paper investigates the consequences for other human activities in outer space of ASAT weapon systems and the conversion of space into a new domain for fighting wars. We focus on the consequences of the weaponization of space on the population dynamics of orbital debris. We use the model of satellites and debris developed by Bongers and Torres (2021), and extend it by the inclusion of an exogenous variable representing a military shock. This shock could be a single ASAT test and the destruction of a satellite, or a war in which a large number of satellites are destroyed. As a consequence of an ASAT test, the population of debris jumps suddenly, increasing the risk of collision with other satellites and spacecraft. This increases the cost of operating a commercial satellite, as this cost includes the possibility of losing the satellite through a collision, resulting in a reduction in the number of commercial satellites. Finally, we simulate a military conflict between nations with ASAT capabilities that results in the destruction of 250 satellites and the creation of enormous clouds of debris. This would have catastrophic consequences for human activities in outer space, not only in the short run but also in the long run, accelerating the Kessler syndrome with an endogenous growth of orbital debris.

The structure of the body of the paper is as follows. Section 2 describes the main characteristics of anti-satellite weapons and their classification, and the tests carried out by the different nations. Section 3 reviews the relationship between the weaponization of outer space and orbital debris. Section 4 presents a model of satellites and orbital debris augmented with a military exogenous shock. Section 5 simulates the calibrated model by considering shocks produced by an ASAT test or a war between the main spacefaring nations. Finally, Section 6 presents the main conclusions.

Anti-Satellite (ASAT) Weapons

An ASAT weapon is a weapon system designed to make unserviceable or to destroy satellites or other spacecraft in Earth's orbit. The logic for developing this type of weapon system is that satellites and other spacecraft, military or civil, of potential enemies are high value assets for warfare, and, hence, key potential targets in the case of conflict. The history of ASAT weapons starts at practically the same time as human beings began to access outer space, and the aim of these weapons was to gain the capacity to destroy enemy satellites (Koplow 2009). During the first years of space conquest, access to space was driven by the two big powers (namely the US and the Soviet Union), leading to a replication in space of the Cold War on Earth. Both nations soon discovered the strategic military importance of outer space, and, immediately, they both started to develop ASAT weapons in an incipient space arms race. The initial technological strategy for the development of ASAT weapon systems was different in the two countries. Whereas the US focused on the development of DA-ASAT missiles, the Soviet Union concentrated its efforts in developing co-orbital ASAT weapons (i.e. Istrebitel Sputnikov or fighter satellites). Grego (2012) reviews the history of anti-satellite weapon programs and the international diplomatic efforts to prevent an arms race in space. Nowadays, only a few countries have the capacity to launch spacecraft, and fewer still have the capacity to destroy spacecraft. ASAT weapon systems have been developed by the US, Russia (previously the Soviet Union), China, India, and, to some extent, Israel, although the number of countries and non-state actors that have some capacity to interfere in the normal functioning of satellites is high. In recent years, the main spacefaring countries have renewed their interest in developing ASAT weapon systems further, producing a space arms race among the US, Russia and China.

Several international initiatives have surged to limit the weaponization (militarization is accepted with no restriction) of outer space. The United Nations COPUOS (Committee on the Peaceful Uses of Outer Space) was established in 1959 as a basis for international cooperation among the spacefaring nations in the exploration of outer space. The Outer Space Treaty (OST), signed in 1967, states that space must be used for peaceful purposes. However, the OST banned the military use of outer space in a very lax way. In truth, the OST only banned the use of nuclear and mass destruction weapons in outer space (Article IV), leaving any other military activity insufficiently regulated, although the Treaty calls for the peaceful use of space. As indicated by Bourbonniere and Lee (2008), the placement of conventional weapons, including systems with nuclear drives, does not violate the Treaty. After some ASAT tests with nuclear weapons were carried out during the period 1958-1962 by the US and the Soviet Union, the Partial Test Ban Treaty, formally titled The Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water of 1963, banned such tests. More recently, two major spacefaring countries, China and Russia, presented a proposal in the year 2008 to 'define and prohibit the proliferation of weapons in space', which was named the PPWT (Treaty on the Prevention of the Placement of Weapons in Outer Space, the Threat or Use of Force against Outer Space Objects). However, this proposed Treaty was rejected by the US, leading to a space arms race and accelerating the development of space weapon systems by China and Russia. Chow (2018) argues that space arms control proposals such as the PPWT are bound to fail, and, instead, the control should be hybrid, consisting of a prohibition on any satellite from being positioned too close to another country's satellite combined with the authorization of pre-emptive self-defense as a last resort countermeasure. Shimabukuro (2014) argues that the first power position of the US in the global order and its pre-eminence in space is the primary cause of the rejection of any treaty preventing a space arms race.

ASAT weapons can be classified into five categories: nuclear weapons, direct-ascent weapons, orbital systems, energy weapons, and jamming systems.[6]

Nuclear Weapons

Missiles with nuclear warheads can be used as ASAT weapons, as they have the ability to reach outer space and explode at high altitude. Indeed, the first ASAT weapons to exist consisted of the detonation of a nuclear warhead at high altitude. This was a natural follow-up on the development path, as rockets for launching satellites were missiles without a warhead. In the early years of the conquest of space, between 1958 and 1962, both the US and the Soviet Union conducted a number of nuclear tests at high altitude, with harmful negative effects on both the Earth and outer space.[7] Table 1 shows the nuclear tests carried out at high altitude (only those tests at an altitude above the Kármán line, fixed at 100 km, are considered). The US conducted three space nuclear tests in 1958 and another three in 1962, whereas the Soviet Union conducted two in 1961 and another two in 1962 (Johnston 2009; Grego 2012).[8]

In 1963, atmospheric and exoatmospheric nuclear tests were banned by the Partial Test Ban Treaty. Later, in 1967, Chapter IV of the OST banned the stationing and use of weapons of mass destruction, including nuclear weapons, in space. Finally, the Comprehensive Nuclear Test Ban Treaty, established in 1996, prohibits all kinds of nuclear explosions, over- or underground, underwater, and in the atmosphere. However, in spite of the prohibitions in all these Treaties, it remains true that nuclear missiles form part of the stock of weapons of several nations and can already be used as ASAT weapons in the case of conflict, with each nuclear warhead having the power to disable a large number of satellites indiscriminately, including the country's own satellites.

Table 1. Nuclear explosions in space.

Date	Country	Name	Power	Altitude
27 August 1958	US	Argus-I	1.7 kt	200 km
30 August 1958	US	Argus-II	1.7 kt	240 km
6 September 1958	US	Argus-III	1.7 kt	540 km
27 October 1961	Soviet Union	Test-127	1.2 kt	150 km
27 October 1961	Soviet Union	Test-128	1.2 kt	300 km
9 July 1962	US	Starfish Prime	1.4 Mt	400 km
20 October 1962	US	Checkmate	7.0 kt	147 km
22 October 1962	Soviet Union	Test-184	300 kt	290 km
28 October 1962	Soviet Union	Test-187	200 kt	150 km
1 November 1962	US	Kingfish	410 kt	100 km

Source: Johnston (2009), Grego (2012).

Direct-Ascent (DA-ASAT) Weapons

A second type of ASAT weapon is a direct-ascent (DA) weapon system. These consist of a modified or specific missile that can reach high altitudes well above 100 km. These missiles can directly hit a spacecraft target (kinetic weapon) or destroy or damage a spacecraft by the explosion of the warhead in a wide-ranging area. This is the simplest and most accessible ASAT weapon, as little modification is needed to allow standard long-range missiles, anti-ballistic missiles and anti-aircraft missiles to reach outer space. These weapons can be used to destroy satellites in Low Earth Orbit (LEO, up to 2,000 km), but they are not able to attack satellites in MEO or GEO.[9] The missiles can be launched from a static ground position, a ground mobile system, a ship, or an aircraft. This type of weapon is expected to generate a large number of fragments, from both the weapon itself and from the destruction and fragmentation of the target satellite. Four nations have conducted DA-ASAT tests: the US, Russia, China, and India (see Table 2).

At the end of 1950s, the US developed two ASAT missiles launched from an aircraft: the High Virgo and the Bold Orion (Pfrang and Weeden 2020f). The first true DA-ASAT tests were conducted by the US in 1959, when the first interception of a satellite by a missile was performed, and just two years later the first human-made spacecraft was successfully launched. Previously, on 19 December 1958, a High Virgo missile was launched from a B-58 bomber, using Explorer 4 as the target. A second test used a Bold Orion missile launched from a B-47 bomber on 13 October 1959. The target was a malfunctioning radiation observation satellite, Explorer 6, at an altitude of 252 km. The missile did not hit the satellite, and no additional information is available about its detonation.

During the 1960s, the US developed three DA-ASAT programs: the Hi-Hoe, as part of the Pilot project, the Nike Zeus, and Program 437 (Pfrang and Weeden 2020f). The Hi-Hoe was a missile launched from a fighter aircraft (a modified F-4 Phantom), whereas the Nike Zeus and Program 437 were ground-based.[10] In the 1980s, the US developed another DA-ASAT weapon system launched from an aircraft (Grego 2012; Pfrang and Weeden 2020f).[11] The first launch of the new anti-satellite missile took place in January 1984. On 13 September 1985, an ASM-135 missile was launched, with the target being the Solwind P78-1, a US gamma ray spectroscopy satellite orbiting at 555 km with a weight of 850 kg. The target satellite was destroyed by the missile, and it was estimated that 1,150 fragments of debris were generated by this test.[12] More recently, the US has modified an SM-3, launched from a ship, with ASAT capabilities. On 21 February 2008, the US conducted another DA-ASAT test, using as a target a malfunctioning US intelligence satellite, U.S.A-193 (with a weight of 2,300 kg) and a naval RIM-161 Standard Missile 3 (Pfrang and Weeden 2020f). The test was carried out at an altitude of 247 km, and produced a surprisingly low number of trackable fragments (174 fragments) according to the USSC.

Little is known about Soviet Union projects for developing DA-ASAT weapon systems, and no information is available about tests, which is partly explained by the focus of the Soviet Union on developing orbital weapon systems.[13] Nevertheless, more recently Russia has taken a more active role in developing DA-ASAT weapon systems, and during the 2010s a new missile, the PL-19 Nudol, was developed, and several tests have very recently been done.[14]

As of 2021, Russia and China were still developing more advanced non-kinetic ASATs. Russia is specifically developing a more advanced version of the Nudol system that operates in the LEO and can move between orbital paths, threatening more satellites than do weapons limited to just one orbital path. On November 2015, Russia conducted its first test with the Nudol system, and this was followed by three other tests in December 2018 and in April and December 2020 (Kommel and Weeden 2020). The last DA-ASAT test was conducted by Russia in November 2021, with the destruction of a defunct Soviet satellite (Cosmos-1408) at an altitude of 485 km, with an initial estimation by the USSC of 1,500 pieces of tracked debris (NASA 2022).

China was the third country to test DA-ASAT weapon systems (Weeden 2020a).[15] The most important test by China took place on 11 January 2007, with the destruction of the Chinese Feng-Yun 1C weather satellite (which had a weight of 750 kg and was at an altitude of 865 km), and this resulted in the creation of 3,449 catalogued pieces of debris (NASA 2007). The devastating effects of

Table 2. Direct-ascent ASAT tests.

Date	Country	ASAT	ASAT type	Target	Altitude	Catalogued debris
19 December 1958	US	High Virgo	B-58 bomber	Explorer-4	320	0
13 October 1959	US	Bold Orion	B-47 bomber	Explorer-6	251	0
25 July 1962	US	Hi-Hoe	F-4 Phantom	Unknown	1,600	0
17 December 1962	US	Nike Zeus	Ground	None	185	0
15 February 1963	US	Nike Zeus	Ground	None	277	0
24 May 1963	US	Nike Zeus	Ground	Agena D	370	0
4 January 1964	US	Nike Zeus	Ground	None	146	0
14 February 1964	US	Program 437	Ground	Rocket body	1,000	0
1 March 1964	US	Program 437	Ground	Unknown	674	0
21 April 1964	US	Program 437	Ground	Unknown	778	0
28 May 1964	US	Program 437	Ground	Unknown	932	0
16 November 1964	US	Program 437	Ground	Unknown	1,148	0
5 April 1965	US	Program 437	Ground	Rocket body	826	0
31 March 1967	US	Program 437	Ground	Unknown	484	0
15 May 1968	US	Program 437	Ground	Unknown	823	0
21 November 1968	US	Program 437	Ground	Unknown	1,158	0
28 March 1970	US	Program 437	Ground	Unknown	1,074	0
21 January 1984	US	ASM-135	F-15 aircraft	None	1,000	0
13 November 1984	US	ASM-135	F-15 aircraft	Star	1,000	0
13 September 1985	US	ASM-135	F-15 aircraft	Solwind *P*-78	555	1,150
22 August 1986	US	ASM-135	F-15 aircraft	Star	1,000	0
29 September 1986	US	ASM-135	F-15 aircraft	Star	1,000	0
5 July 2005	China	SC-19	Ground	None	LEO	0
6 February 2006	China	SC-19	Ground	None	LEO	0
11 January 2007	China	SC-19	Ground	Feng-Yun 1C	865	3,449
21 February 2008	US	SM-3	Ship-based	U.S.A-193	247	174
11 January 2010	China	SC-19	Ground	CSS-X-11	250	0
15 May 2013	China	DN-2	Ground	Unknown	30,000	0
18 November 2015	Russia	PL-19 Nudol	Ground	Unknown	100	0
30 October 2015	China	DN-3	Ground	Unknown	Unknown	0
December 2016	China	DN-3	Ground	Unknown	Unknown	0
August 2017	China	DN-3	Ground	Unknown	Unknown	0
February 2018	China	DN-3	Ground	Unknown	Unknown	0
23 December 2018	Russia	PL-19 Nudol	Ground	Unknown	500	0
27 March 2019	India	PDV-MK II	Ground	Microsat-R	300	129
15 April 2020	Russia	PL-19 Nudol	Ground	Unknown	500	0
16 December 2020	Russia	PL-19 Nudol	Ground	Unknown		0
15 November 2021	Russia	PL-19 Nudol	Ground	Cosmos-1408	485	1,500

Source: Pfrang and Weeden (2020f), Kommel and Weeden (2020), Weeden (2020a), Weeden (2020b).

this test come not only from the high number of fragments, but also from the high persistence of the fragments in orbit, given the high altitude of the explosion (Jonhson et al. 2008).[16]

Finally, the last country to join this club was India. India joined in 2019, with an DA-ASAT test in March 2019 that destroyed Microsat-R at an altitude of 300 km (Pfrang and Weeden 2020b). This test created a reported 129 tracked pieces of debris, but given the low altitude of the test, the decay rate is high (Jiang 2020). So, despite the end of the Cold War era, more and more nations have become involved in a space arms race that is resulting in the rapid proliferation of advanced space weaponry. Table 2 summarizes the DA-ASAT tests conducted by these four countries (excluding sub-orbital tests).

Orbital Weapon Systems

Another type of ASAT weapon is an orbital system or satellite-based weapon system. Several types of orbital weapon systems (OWS) have been planned or developed, including killer satellites, battle-stations, and active inspector systems. A killer satellite is a satellite used as a kinetic weapon that can be directed to collide with a target, or an armed satellite that can explode in the vicinity of the target. Killer satellites can be placed in orbit at any time, left in stand-by and then activated to destroy a target during a conflict, or they can be launched when the target passes over the launch site. These orbital weapon systems can be as simple as a kinetic kamikaze device or a more sophisticated satellite with robotized arms or other tools to damage, interfere with, or disable the target satellite. Space battle-stations are spacecraft armed with some type of long-range weapon, such as a cannon, missile, laser or other throwable object. OWS are more complex than DA-ASAT weapons, but they can attack targets not only in LEO, but also in MEO and GEO.

One key characteristic of this type of ASAT weapon system is that it is almost impossible to distinguish the weapons from ordinary satellites. They can carry a subsatellite that is only deployed in case of attack, and they can be launched in the same rocket as other civil satellites. Although information is very short for security reasons, it is assumed that some spacefaring countries have orbital weapon systems, and this is already confirmed in the cases of the US, Russia, and China, although publicly available information about these systems is very limited. As with other ASAT weapons, the US and Russia (previously the Soviet Union) are the leading countries in developing this type of weapon system. Chow (2018) indicates that China started to develop orbital ASAT weapons in 2008, although little information is available on this program.

OWS were the priority for the Soviet Union ASAT program, while the US concentrated initially on the development of DA-ASAT weapons. Nevertheless, both countries launched various OWS programs in the 1960s and 1970s, although these failed and did not become operational.[17]

During the 1960s the Soviet Union also developed the so-called Istrebitel Sputnikov (IS, Satellite Destroyer) co-orbital systems (Grego 2012). During the period 1963 to 1971 the USSR conducted seven tests with the IS system consisting of the close approach of an interceptor to a target, with the detonation of the interceptor vehicle in the kill area of the target. Indeed, the first successful ASAT satellite interception was carried out by the Soviet Union in October 1968, with Cosmos 252 exploding and destroying the target Cosmos 248. The tests were resumed in 1976 and 1977, with eight additional tests, reaching an altitude of 1,600 km. During the 1980s, the Soviets developed a new system, called Naryad, which was capable of inserting kill vehicles at an altitude of more than 38,000 km. The tests of the new system were conducted during the period 1978 to 1982. It is suspected that Cosmos 2499 is another OWS, and a total of 18 pieces of debris produced by this satellite have been catalogued by the SSN (Pfrang and Weeden 2020c).

Although little information about them is available, Russia has developed another series of military satellites, called Sputnik Inspectors, with rendezvous and proximity operations (RPO) capabilities (see Weeden 2019; Pfrang and Weeden 2020c, 2022d). Cosmos 2519 and Cosmos 2542 have RPO capabilities. These satellites carry subsatellites (Cosmos 2521 and Cosmos 2543, respectively), that can approach a target for inspection.[18] The last ASAT test with this type of space weapon was supposedly made by Russia on 15 July 2020, according to the USSC.

The US has also developed OWS for LEO and GEO (Pfrang and Weeden 2020e). In 2005 U.S.A-165, a small satellite with RPO capability, was launched. Another American OWS is the Mitex system, launched in 2006, which consists of one mother satellite (U.S.A-189) carrying two inspection satellites (U.S.A-187 and U.S.A-188). These are microsatellites that can approach and examine or attack other satellites without being detected (Pfrang and Weeden 2020g). Another program was the Exoatmospheric Kill Vehicle (EKV), which was cancelled in 2019 and replaced by a new program called the Next Generation Interceptor.[19] Finally, the X-37B is an experimental vehicle used to deploy small satellites and for other unknown operations.[20]

China is the third country developing OWS, and it is suspected that China has an important program for developing orbital ASAT weapons. A first test was conducted by China in June 2010, with the SJ-12 attacking the SJ-6F and causing it to move away from its orbital regime. This test is interpreted as the development of a satellite that has the ability to attack a target satellite and move it away from its position. A second test was conducted on 18 August 2013, with the SJ-15 attacking the SY-7 (Pfrang and Weeden 2020a).

Table 3. Orbital ASAT tests and RPO.

Date	Country	ASAT	ASAT type	Target	Altitude	Debris
15 June 1974	USSR	Salyut 3	Space battle-station	Unknown	270	0
1 November 1963	USSR	Polyot 1	Killer payload	None	300	0
12 April 1964	USSR	Polyot 2	Killer payload	None	300	0
27 October 1967	USSR	Cosmos 185	Killer satellite	None	Unknown	Unknown
20 October 1968	USSR	Cosmos 252	Killer satellite	Cosmos 248	Unknown	252
23 October 1970	USSR	Cosmos 375	Killer satellite	Cosmos 373	Unknown	147
6 September 1986	US	Delta 180	Killer payload	Delta 2 R/B	220	16
23 December 1994	Russia	Naryad-V	Killer satellite	None	Unknown	27
June 2010	China	SJ-12	Inspector satellite	SJ-6F	Unknown	Unknown
18 August 2013	China	SJ-15	Inspector satellite	SY-7	Unknown	Unknown
August/September 2017	Russia	Cosmos 2521	Inspector satellite	Cosmos 2523	Unknown	Unknown
December 2019	Russia	Cosmos 2536	Killer satellite	Cosmos 2535	605	27

Source: Grego (2012), Weeden (2019), Pfrang and Weeden (2020c, 2020d, 2020e, 2020f, 2020g).

Military orbital systems have certain key characteristics. First, governments do not provide information about the launches of such spacecraft. Second, it is unknown how many such systems there are. They can stay deactivated for a long period. Even derelict satellites could be OWS to be activated in case of conflict. RPO capabilities are progressing rapidly. This is not specific military technology, as it also has commercial and other purposes, such as docking in space-stations, orbital assembly, and in-space refueling, repair, and upgrading. However, the military interest in this technology is evident, not only for ASAT weapons, but also to inspect satellites and collect intelligence (Weeden 2019). It is difficult to distinguish orbital weapons from ordinary or derelict satellites, which adds more complexity to the problem. Table 3 shows the tests (some of them suspected) of orbital systems conducted by the Soviet Union (Russia), the US, and China.

ASAT Energy Weapons

ASAT energy weapons consist of a laser, and the objective is to blind the sensors of enemy satellites. This type of weapon is not intended to destroy enemy satellites physically, but to disable, temporarily or permanently, their electronic components and sensors. For instance, laser weapons can disrupt, degrade, or damage satellites and their sensors (Grego 2012). A laser beam as an ASAT weapon has been developed and tested at different stages by the main powers (the Soviet Union/Russia and the US), and more recently by China. These energy weapons can be ground-based, airborne or even space-based. Russia, the US, and China are countries that have been confirmed as having this type of weapon.[21]

ASAT Jamming Systems

Finally, as on Earth, there is another type of ASAT weapon that consists of using jamming systems against enemy satellites to prevent their use. Satellite jamming can be defined as an electronic ASAT weapon system that interferes with communications between the satellite and the Earth stations (up-link and down-link) by emitting noise of the same radio frequency. Like ASAT energy weapons, ASAT jamming systems do not physically destroy the satellite, but in this case there is no physical damage to the target and the attack is temporary (Wilgenbusch and Heisig 2013). Therefore, this ASAT system is no different from its counterpart on Earth, and therefore has the key characteristic that its use does not produce orbital debris, and that its effects are reversible, as communications are restored after the attack without any damage to the satellite or Earth-based stations (Grego 2012). An example of this type of ASAT attack is GPS spoofing.[22]

ASAT jamming systems have been developed not only by the main military powers (Velkovsky, Mohan, and Simon 2019) but also, because of the relative easy access at low cost to this technology, by small nations, allowing them to have some limited ASAT capability. Wilgenbusch and Heisig

(2013) show that countries as Cuba, Syria, Indonesia, Libya, and Ethiopia have interfered with satellite signals. Finally, although satellites are difficult to protect physically, they can be more easily protected from jamming than other military electronic devices on Earth. The main spacefaring nations are also developing anti-ASAT jamming systems.

Orbital Debris and ASAT Tests

NASA (2021) defines orbital debris as 'any human-made object in orbit that no longer serves a useful purpose, including spacecraft fragments and retired satellites.' In short, orbital debris is a type of space pollution, with some particular characteristics that make it different from other types of pollution on Earth, and it can have dramatic consequences for commercial and other activities in outer space (Liou and Johnson 2006). Launching satellites and carrying out other operations in orbit generates debris that can collide with operational satellites and other spacecraft, with fatal consequences. Even small pieces of debris with little mass can have catastrophic consequences for a spacecraft with which they collide, because of the high velocities. On the other hand, space debris can reach an amount that is self-propagating, as collisions between pieces of debris create more debris. This is the so-called Kessler syndrome, representing a scenario of cascading collisions (Kessler and Cour-Palais 1978). Debris is generated from different sources, and includes parts of launch vehicles and rocket bodies, non-functional satellites, the results of the intentional or accidental breaking-up of satellites and rocket bodies, and even tools lost by astronauts. Most debris (around 85%) is at LEO altitude (below 2,000 km), with peak concentration around an altitude of between 700 and 900 km (NASA 2020).

The primary non-intentional cause of orbital debris is in-orbit explosions, which are related to the residual fuel in the tanks of rockets' upper stages or derelict satellites abandoned in orbit (Hall 2014). The extreme conditions in outer space quickly cause mechanisms and devices to deteriorate, leading to leaks in the fuel mixing components, which provoke accidental explosions that break up rocket bodies and other spacecraft and generate a large number of fragments that travel around the initial orbit at hyper-velocity (above 10,000 kilometers per hour). The other important source of orbital debris is ASAT tests, as advanced by Marshall (1985). Besides accidental break-ups, spacecraft interceptions by Earth-based missiles have been a major contributor in the recent past, contributing to boosting to the population of debris, whereas other types of ASAT weapons (such as directed energy weapons or jamming systems) produce little to no debris. Orbital weapon systems such as interceptor satellites also produce debris, but a significant lower quantity than DA-ASAT weapons. As indicated above, DA-ASAT tests producing large numbers of pieces of debris, some of them at high altitude, have been conducted by four countries: the US, Russia, China, and India. One single event, the intentional destruction of the Chinese Feng-Yun 1C satellite by a missile in January 2007, increased the population of trackable space debris (those pieces larger than 10 cm) by 30% (OECD 2020, 19). In total, ASAT tests accounted for about 41% of orbital debris up to the year 2010 (Wright 2011, 13), and this percentage is much higher if the DA-ASAT test conducted by China in 2007 and the most recent test carried out by Russia in 2021 are also considered.

Figures 1 and 2 plot the evolution of the number of tracked objects in orbit from 1957 to 2021. Figure 1 shows how the total number of catalogued objects has evolved over time (the amount of debris is larger than the amount of catalogued objects; the US Space Surveillance Network (SSN) can only track objects larger than 5-10 cm in LEO and larger than 1 m in GEO, and only objects with a known origin are catalogued). Some jumps in the number of objects can be observed in some years, and these are caused by accidental break-ups, explosions, and collisions, but also by the deliberate destruction of targets in ASAT tests. The number of catalogued objects has been increasing steadily, except in some years such as 1989 and 1990, coinciding with the disintegration of the Soviet Union, which significantly decreased the number of launches. The decline of the total number of objects in orbit in these two years was due to the fact that de-orbit both intentionally and by atmospheric drag was larger than the new objects in orbits from launches and other sources.[23] However, the creation of debris has accelerated in the second half of the decade beginning in 2010,

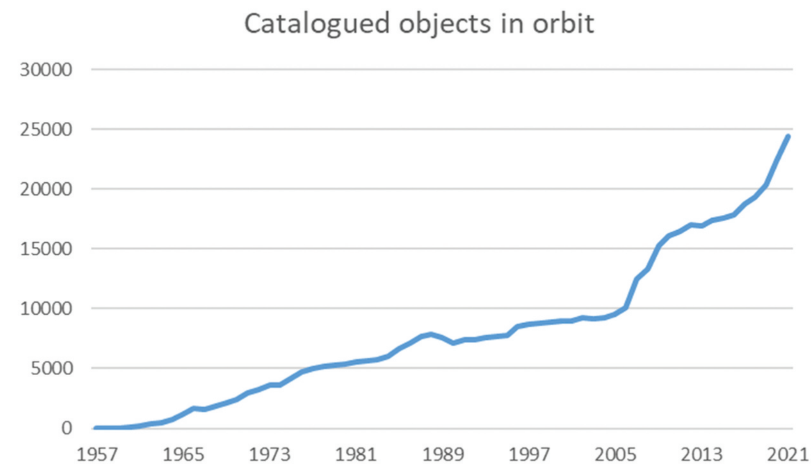

Figure 1. Catalogued objects in orbit 1957-2021. Source: US Space Surveillance Network (SSN).

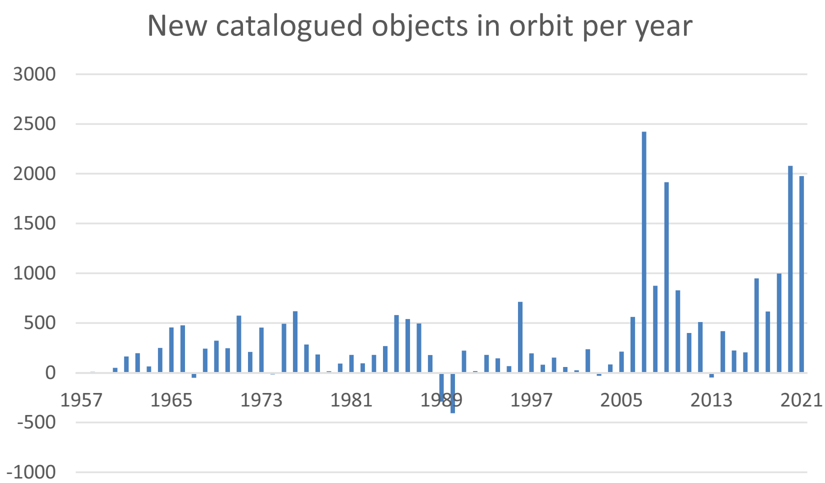

Figure 2. New catalogued objects in orbit per year. Source: US Space Surveillance Network (SSN).

and in the last three years due to both collisions with debris and additional DA-ASAT tests. Figure 2 plots the number of new catalogued objects in orbit each year, with significant increases in the last two decades. There are three main reasons for this. First, there is an increasing number of accidental collisions between satellites and debris (the most important has been the collision of a commercial American communication satellite, the Iridium-33, with Cosmos 2251, a derelict Soviet Union military satellite, in 10 February 2009). Second, the number of DA-ASAT tests involving the physical destruction of the target has increased significantly during the last two decades, as the number of countries with this type of weapon system has expanded. Third, tracking technology is constantly progressing. The Space Fence radar of United State Space Force (USSF) becoming operational in March 2020 has increasing the capability of tracking and accurate measurement of space objects. Finally, the number of new catalogued objects in orbit will experience a significant growth in the next years with the advent of constellations of satellite at LEO. As of August 2002, the SpaceX Starlink constellation has over 2,793 operational satellites (of 3,055 launched) from a planned total of 12,000 satellites by 2026 (Berry 2022).

The harmful effects of DA-ASAT tests over time depend heavily on the altitude of the target being destroyed, whereas the number of new fragments depends on the weight of the target. At low altitude, the debris produced by a test has a short life because of atmospheric drag, as the fragments rapidly lose altitude and burn up on re-entry to the atmosphere. However, fragments produced at high altitude are long-lasting, remaining in space for hundreds of years. King-Hele (1987) estimated that the lifetime of space objects varies as follows: 1 day at 200 km, 1 month at 300 km, 1 year at 400 km, 10 years at 500 km, 100 years at 700 km, and 1,000 years at 900 km. On the other hand, the distribution of debris as a function of altitude is not homogeneous. Debris is concentrated in the range of 700 to 900 km (NASA 2020), and this is also the most congested orbit for operational satellites. To date, the highest altitude DA-ASAT test was carried out by China in 2007, at an altitude of 865 km, which is the most polluted orbit and where fragments will remain for almost one thousand years, (NASA 2020).

A Model for Satellites and Space Debris

The economic implications of orbital debris have been extensively studied in the literature. As pointed out by Weinzierl (2018, 186) the outer space is already 'congested, contested and competitive', arising a number of market failures. One of these market failures takes the form of a negative externality in the form of orbital debris. Seminal papers studying the economic consequences of orbit debris are Adilov, Alexander, and Cunningham (2015, 2018) and Macauley (2015). Adilov, Alexander, and Cunningham (2015) find that the numbers of satellites and launches are higher than the social optimum as firms do not take into account the negative externality of debris generated by their activities in space. Adilov, Alexander, and Cunningham (2018) use a net present value approach to determine that the threshold level of debris for economic viability is lower than the 'Kessler syndrome' level identified by Kessler and Cour-Palais (1978). Macauley (2015) evaluates different technological strategies to mitigate debris generation and/or collision risk, including maneuvering capability, graveyarding capability and shielding. Klima et al. (2016) used a game theory approach whereby spacefaring agencies have the option of implementing costly active debris removal interventions that benefit all spacefaring agents or waiting for other agents carry out the work. A game theory approach for analyzing the orbital debris problem is provided by Grzelka and Wagner (2019) and. Béal, Deschamps, and Moulin (2020). Rouillon (2020) considered a model with a constant rate of satellite launches and concluded that the number of satellites is an inverted-U shape function of the launch rate. Rao, Burgess, and Kaffine (2020) developed a model with infinity-lived satellites to study the implications of Pigouvian taxation consisting of an international orbital-use fee. Adilov, Alexander, and Cunningham (2020) simulated the quantity of orbital debris under different policies, including a launch tax, voluntary debris mitigation, and active debris removal policies. Bongers and Torres (2021) develop a dynamic investment model and identifies a threshold value for the number of satellites in orbit to prevent further increase in orbital debris. However, to the best of our knowledge, no quantitative analysis on the impact on space debris has been done in the literature.

To make a quantitative assessment of the impact of ASAT weapons in the outer space environment, we use a physical – economic model that accounts for the interaction between satellites and debris. The model extends the one developed by Bongers and Torres (2021) by including an exogenous debris military shock. This military shock could be the destruction of a single satellite (a DA-ASAT test) or the destruction of multiple satellites (war among spacefaring nations with ASAT capabilities). The model considers a competitive market in which satellite-operating firms maximize their profits. Activity in outer space provokes a negative externality in the form of pollution (human-produced space debris or junk). The model considers the possibility of collision and the risk of the destruction of a satellite colliding with space debris.

It is assumed that firms with infinite life operating in outer space maximize the sum of their discounted profits, defined as $_t$

$$max\, E_0 \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \Pi_t \tag{1}$$

where E_0 is the expectation operator at time 0, $1/(1+r)$is the discount factor, and r is the interest rate. The profits are defined as,

$$\Pi_t = Y_t - cL_t \tag{2}$$

where Y_t represents income from satellite services, and L_t is the number of launches. c represents the cost per launch. For simplicity, we assume that c and r are exogenously given, and that space operating firms have perfect foresight. We assume the following technology function for satellite services:

$$Y_t = S_t^{\alpha} \tag{3}$$

where $\alpha(0 < \alpha < 1)$represents the elasticity of satellite services with respect to the quantity of satellites, and is assumed to be less than one, indicating the existence of decreasing returns for a given demand for satellite services. The stock of operational satellites at period $t+1$, S_{t+1}, is,

$$S_{t+1} = (1-\delta_s)S_t + \eta L_t - X_t \tag{4}$$

where $0<\delta_s<1$ is the depreciation rate of satellites, L_t is the number of launches, η is the number of satellites per launch, and X_t is the number of satellites destroyed in each period by collision with debris (failures or accidental explosions of satellites are included in the depreciation rate). For simplicity, it is assumed that the quantity of satellites per launch is one. Following Farinella and Cordelli (1991), the number of destroyed satellites is given by

$$X_t = \theta D_t S_t \tag{5}$$

where the term $\theta D_t S_t$ gives the number of satellites destroyed in every period by collisions with debris. $\theta > 0$ is a parameter representing the probability of collision. It is assumed that the probability of collision is proportional to the quantity of debris, θD_t.[24] When $\theta D_t = 1$, that is, $D_t < 1/\theta$, this is the Kessler syndrome as defined by Kessler and Cour-Palais (1978) and Adilov, Alexander, and Cunningham (2015), and all spacecraft are destroyed by collisions in the period.

Debris follows an accumulation process depending on the new debris generated in each period. In modelling the debris accumulation process, we consider two sources: destroyed satellites and launches. Unlike any other source of pollution, the dynamics of orbital debris includes a self-propagating mechanism, where pollution generates additional pollution. That is, debris collides not only with satellites but also with other pieces of debris. The law of motion of debris can be defined as:

$$D_{t+1} = (1-\delta_d)D_t + \gamma X_t + \omega L_t + \rho\delta_s S_t + \sigma\theta D_t^2 + Z_t \tag{6}$$

where $\gamma > 0$ is the number of new pieces of debris generated by the destruction of a satellite, $\omega > 0$ is the number of pieces of debris generated by a launch, $0 < \rho < 1$ is the percentage of derelict satellites that remains in orbit, and $\sigma > 0$ is the quantity of new debris generated by self-collisions. As above, we assume that the probability of collision is proportional to the quantity of debris. It is assumed that the debris generated for each launch includes explosions and fragmentations produced by last-stage rockets. The parameter $\delta_d(0 < \delta_d < 1)$ represents the decay rate of debris. This decay rate mainly depends on atmospheric drag and is therefore a function of the altitude of the orbit. The higher the altitude of the orbit (with respect to the Earth), the lower the decay rate. Collisions among pieces of debris are also considered, represented by the term $\sigma\theta D_t^2$, where the probability of collision (θD_t) multiplies the stock of debris. Finally, the law of motion of orbital debris includes an exogenous variable, Z_t, representing ASAT shocks (i.e. military DA-ASAT tests or a war in space).

Spacefaring operators maximize their profits for a given amount of debris. Maximizing (1) subject to (2), (3), (4) and (5), we find that the optimal number of satellites is given by:

$$S_t = \left(\frac{c(r + \delta_s + \theta D_t)}{\alpha \eta A_t} \right)^{1/(\alpha - 1)} \tag{7}$$

resulting in a (negative) function of the amount of debris. As debris accumulates, the risk of collision and the destruction of capital assets in space increases, reducing the expected profits. As shown in expression (7), the effects of debris on the optimal number of satellites adopts the form of a sunk-cost. As long as the probability of collision is sufficiently low, the negative impact of debris on satellite activity will also be very low. However, as the stock of debris increases, the probability of collision during the life of a satellite escalates, increasing the sunk-cost and reducing the equilibrium quantity of satellites. Therefore, the increasing amount of debris is a factor which would increase the total cost of spacefaring firms, and even could compensate the declining cost of launches due to technological progress if the quantity of debris is large enough.

Simulation Results

This section studies the consequences of a military shock for the outer space environment. First, the parameters of the model are calibrated following Bongers and Torres (2021). Then, the calibrated model is used to simulate two scenarios: a DA-ASAT test, and a war between two main powers that implies the destruction of a significant proportion of satellites in orbit.

DA-ASAT Test Simulation

To assess the implications of DA-ASAT military tests on the population of orbital debris and the risk of collision, we simulate the model by considering a shock equivalent to the destruction of a satellite. The number of fragments produced by the destruction of a satellite by a missile depends on several factors, such as the size, mass, and design of the target. As indicated in Table 2, several DA-ASAT tests with the destruction of a target satellite have been carried out by the US, Russia, China, and India. The number of (catalogued) fragments produced by these tests varies from 129 for the Indian test in 2019 (where the target was a microsatellite) to the 3,449 fragments produced by the Chinese test of 2007. These figures correspond to tracked fragments larger than 10 cm. Given these figures, we assume in the simulation that the ASAT test produces 2,000 new fragments of trackable size. According to the NASA standard break-up model, the number of pieces of debris between 1 and 10 cm is 50 times higher. Therefore, the total number of pieces of debris larger than 1 cm produced from a DA-ASAT test is 102,000. Given that the estimated population of debris for the calibration of the model is 934,000, the additional 102,000 fragments would imply an increase in the population of debris of around 11%. As indicated by Wright (2011, 28) based on the NASA standard break-up model, the destruction of a single 10 ton satellite would produce between 5,000 and 15,000 fragments larger than 10 cm, and between 250,000 and 750,000 fragments between 1 to 10 cm. In the test conducted by China in 2007, a total of around 3,500 tracked pieces of debris were produced and it is estimated that another 175,000 fragments between 1 and 10 cm were created (NASA 2007).

Figure 3 plots the impulse response of the number of satellites, calculated as the percentage deviation from the steady state, the estimated number satellites destroyed by collision with debris and the dynamics of new debris following the DA-ASAT test.[25] As can be observed, the creation of new debris reduces the optimal number of satellites in orbit and increases the number of satellites destroyed by collision with debris. The higher probability of collision and the loss of capital assets reduces the expected profits of the satellite operating firms, so that they decrease the number of new launches and do not replace all the satellites that have completed their operational life. In the baseline scenario (no shock), the model predicts that one satellite is destroyed by collision with debris every five years. Adding a new DA-ASAT test, one satellite would be destroyed every 4.5 years. The graph on the right-hand side plots the simulated increase in the amount of debris and the evolution over time of these new pieces of debris. These results are obtained with the benchmark

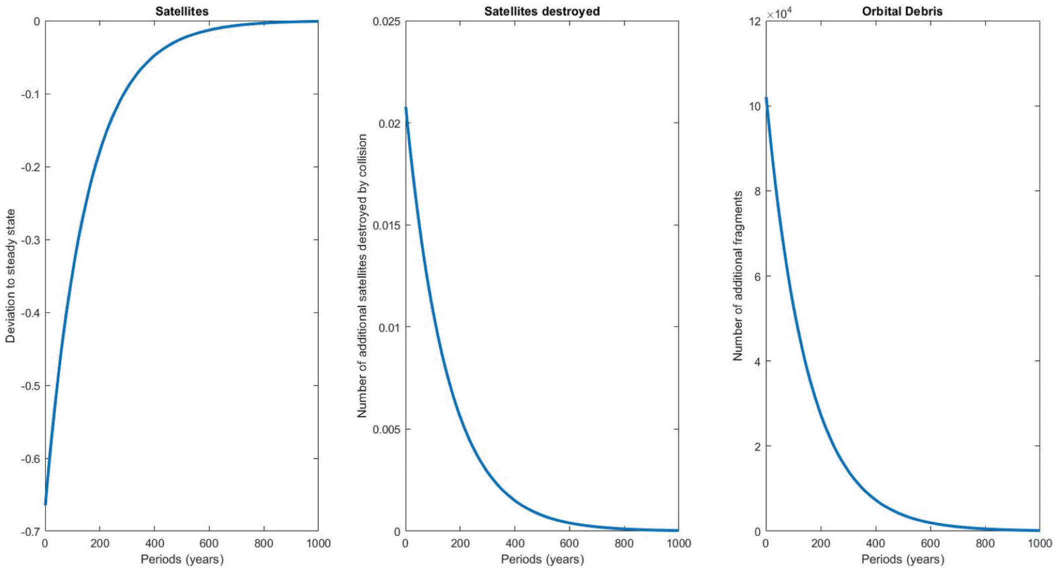

Figure 3. Effects of a DA-ASAT test.

calibration for the debris decay rate, which implies a very persistent effect of the shock: the effects of the test only vanish totally after around 1,000 years. Of course, this will depend on the initial altitude of the cloud of debris. If the test is carried out at low altitude, the effects will be transitory. However, as the altitude increases, the persistence of the shock will also be greater.

The results plotted in Figure 3 are derived from a calibration of the model for a DA-ASAT test to particular altitude. This calibrated altitude of the model corresponds to an average orbit resulting from calculating the different orbits weighted by the number of satellites in each orbit. This is represented by the parameter δ_d, representing the decay rate of debris. This parameter takes a value of 0.0062, corresponding to an average estimated lifetime of 150 years, which corresponds to an altitude of around 800 km (Lewis et al. 2009, 574). The model can be used for simulating the AD-ASAT test at other altitude, resulting in a similar dynamic for the variables except in the number of periods required to return to the initial situation. Summing up, the effects of the shock, mainly its persistence, will depend dramatically on the altitude of the explosion, but in the short run the probability of collision increases depending on the concentration of satellites in the orbit of the test. The above results represent a situation in which the level of debris is low enough, and the increase in debris is also low enough, to avoid the Kessler syndrome. This implies that the additional debris produced by the test tends to zero over time because of atmospheric drag, as no cascade effect is considered. However, it could be the case that the space environment at a particular orbit reaches a point close enough to the Kessler condition for an additional DA-ASAT test to be the trigger for the self-propagation mechanism (Adilov et al., 2000).

A Star Wars Simulation

Next, we simulate a military conflict among two main powers in which space is also part of the battlefield and a significant number of satellites are destroyed. This could be a real scenario in the case of a war between the US and China, as for each of them the enemy's satellites would be primary targets, given their strategic value in the case of a conflict between these two nations. Military satellites are vital for enemy military capacity, and, hence, enemy satellites are potential targets. Also, a country's own military satellites will be the targets for the enemy if there is a conflict between spacefaring nations. As of December 2021, the number of active US satellites was 2,944 and the number for China was 499, according to the Union of Concerned Scientists Satellite Database.[26] A war would imply the destruction of a high number of satellites, both military and civil, given that civil satellites can also be used for military purposes. Our simulation assumes that 250 satellites (that is, around 10% of the operational satellites of both countries) are attacked and destroyed during the war.

A war in space, with the physical destruction of satellites, would create large amounts of debris, which would be an additional threat for the surviving satellites and for satellites from other nations not involved in the conflict. Furthermore, given the persistence of debris, the threat for any surviving satellite would remain even when the war ended. In the simulation, we assume that the number of pieces of new debris (fragments larger than 10 cm) generated from the destruction of each satellite is 2,000, as in the previous shock, and, according to the NASA standard break-up model, the number of pieces of debris between 1 and 10 cm is 50 times higher, that is, there are an additional 100,000 fragments that are extremely dangerous as they cannot be tracked and avoided by maneuvering actions. This means that the total additional number of pieces of debris resulting from the war is 25,500,000 (fragments larger than 1 cm). Given that the pre-war number is estimated to be 934,000 fragments, the war increases the amount of debris by around 2,700%. This increase is extremely high, but it is important to remember that one single event, the ASAT test conducted by China in 2007, increased the amount of debris by around 30% (OECD 2020, 19).

The current ASAT technology has proved that satellites are easy to destroy and difficult to protect. It is obvious that from a military perspective, the operational capacity of forces would be greatly affected. Without long-range communication, reconnaissance and GPS for drones and guided bombs, and even weather information, the operational capacity of modern forces would be significantly reduced. However, it is not only military satellites that would be targets, but also civil satellites, given the dual role of any space technology. Apart from military considerations, a war in space would have dramatic consequences for the human use of the near-Earth orbit, not only during the armed conflict but for a number of years after the war had ended. This is a direct consequence of the new cloud of debris created by the war, which is long-lasting. In the short run, high value services from satellites would be interrupted, which would have a harmful effect on normal life on Earth for the whole of humankind. Nevertheless, the problems arising from a war in space do not finish here. The physical destruction of satellites would create a large amount of debris, which would be an additional threat for surviving satellites. This would increase the risk of collision between operational satellites and debris but also between fragments of debris, which could accelerate the Kessler syndrome with cascading collisions that would make space useless for any human activity.

Figure 4 plots the difference between the war and the non-war scenarios in terms of the number of satellites, the number of satellites destroyed, and the quantity of debris. We consider the case where the war takes place in period 10. We can observe a sudden increase in the amount of debris compared to the pre-war scenario produced by the destruction of satellites during the conflict. However, after the war, the difference in the amount of debris between the two scenarios increases steadily. This is true in spite that the decay of debris is higher after the war, given the higher number of fragments, and that the number of satellites is lower after the war, decreasing the probability of collision and the production of additional debris. However, the rise in launches to replace destroyed satellites produces additional debris. Although the number of satellites partially recovers after the war, the large amount of debris increases the risk of collision and the number of satellites destroyed. This would lead to an unsustainable situation in the Earth orbit, with the number of satellites decreasing toward zero, as the probability of collision approaches one.

Simulation of the model show that the destruction of a large number of satellites would generate an unprecedented cloud of debris. This mass of debris would affect all spacefaring nations equally, putting at risk or even destroying all remaining satellites surviving the battle, with no winner. As shown by Figure 4, the number of satellites in orbits begins to recover from the end of hostilities, although they never reach their initial value again, given the higher level of debris. However, around

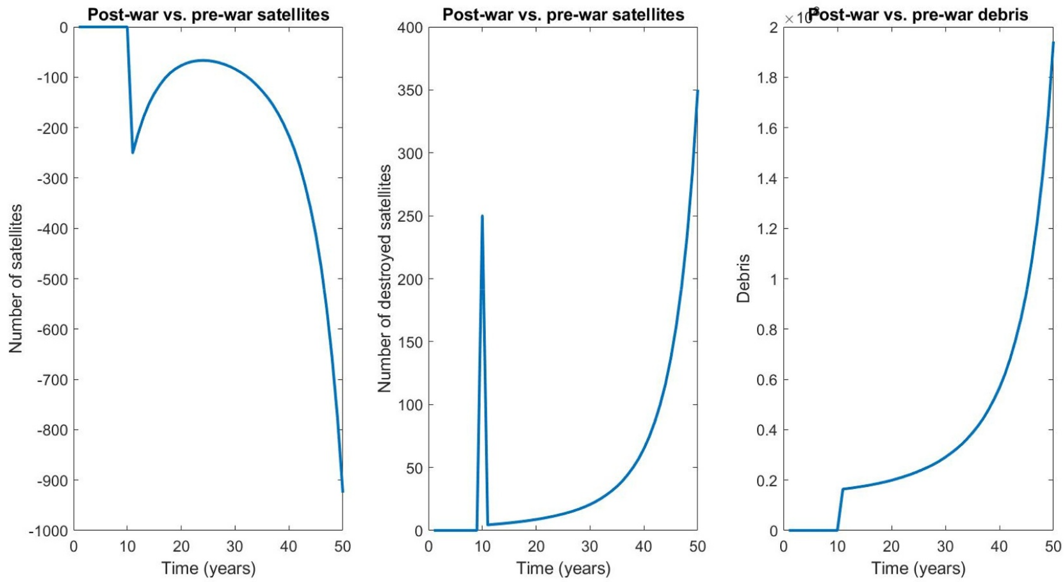

Figure 4. Effects of a war in space with the destruction of 250 satellites. The plots show the difference between a scenario without war and a war scenario by looking at the differences in the number of satellites in orbit, the number of satellites destroyed and the amount of orbital debris between the situation when a war takes place in period 10 and a scenario without war.

15 years after the war, the number of satellites starts to decline. This is explained of the fact that the increasing number of collisions produces additional debris, leading to a new environment in which the probability of collision is greater than in the pre-war situation. As a consequence, the quantity of debris would increase exponentially, producing more collisions and driving the number of operational satellites to zero around 40 years after the war. The increases in orbital debris would cause the net present value of satellites to tend to zero, as studied by Adilov, Alexander, and Cunningham (2018), making outer space totally useless for any human activity.

Conclusions

The militarization of outer space can be considered as a natural and inevitable process once access to space became technologically feasible, given the wide range of strategic advantages of space for military activities. In principle, it can be argued that the militarization of outer space does not pose any risk in that environment, except by further congesting the orbit and radio spectrum with military satellites in a similar way to other civil and commercial activities. However, the military use of space does not end here, and the weaponization of outer space represents a dramatic hazard even in peace time, because of the impact of ASAT tests on the generation of orbital debris, and the potential limitations on the development of active debris removal vehicles. Space debris is a danger for the exploration and commercial exploitation of outer space, and ASAT tests, especially with direct-ascent weapons, have generated a considerable amount of new debris, aggravating the space junk problem and significantly increasing the risk of collision. In this sense, ASAT weapons have not only increased the amount of orbital debris but can be an obstacle for active debris removal policies.

The weaponization of outer space means that Earth's orbit has become another battlefield for the main powers, as enemy satellites are high-value military assets whose destruction denies the enemy forces critical capabilities. As is recognized by the main powers, space is a new and increasingly important domain for fighting wars. The destruction of enemy satellites, not only military ones but also civil ones as the latter also have a military use, would be critical for winning a war on Earth.

However, a war in space would, in some aspects, be similar to a nuclear war, as the Earth's orbit environment would be destroyed and polluted with millions of pieces of junk. In this hypothetical war scenario all the foes would lose, and the near-Earth orbit would be rendered completely useless for any human activity, with global negative consequences for all nations.

Given the physical characteristics of the outer space environment and the technical characteristics of satellites and other spacecraft, banning or limiting the weaponization of outer space is extremely difficult, if not impossible. RPO capabilities are crucial for the commercial and civil use of space, vital for the development of in-space industries, and compulsory for active debris mitigation actions. However, RPO capabilities have a dual use, and any spacecraft possessing those capabilities is a potential weapon. Furthermore, any object in space with maneuverability capabilities is a potential kinetic weapon because of the high velocities. The global common nature of space, the technical difficulties of tracking space vehicles and identifying their nature, and drawbacks in space situational awareness in spite of recent technological advances, are all factors that add more complexity to any initiative to prevent the further weaponization of outer space and for the implementation of active debris removal policies to protect this environment for humanity.

Notes

1. Low Earth orbit (LEO) is the area of space at an altitude between around 100 and 2,000 km.
2. The use of the SpaceX Starlink satellite constellation by Ukraine for internet access in the war against Russia is an example the technological and operational advantages provided by civil satellites for military and defence activities. Even launch systems using a high-altitude airplane platform developed by private aerospace companies as the Virgin Orbit's LauncherOne, the Orbital Science's Pegasus and the StratoLauch, have a direct military application.
3. Koplow (2009, 1201) pointed out that the US started working on the development of ASAT weapons only a few weeks after the launch of Sputnik I, and that presumably the Soviet Union did the same.
4. Active debris removal vehicles can use a number of alternative technologies, such as robotic arms, nets, space balloons, lasers, etc. All these devices can interfere not only with debris but with any other spacecraft and even some of these technologies are capable of destroying functional satellites.
5. For a view of the issue from the perspective of international law, see, for instance, Zedalis and Wade (1978), Kingwell (1990), Ramey (2000), Maogoto and Freeland (2007), Kuplic (2014), Ford (2017), and Taft (2017).
6. Cyber-attacks can also be considered as ASAT weapons, although they are not space-specific and share the same characteristics as cyber-attacks on Earth.
7. In outer space, because of the absence of atmosphere, nuclear radiation suffers no physical mitigation, and radiation intensity is only reduced by distance.
8. The first nuclear explosions in space were conducted by the US between August and September 1958 as part of Operation Argus, and consisted of the explosion of a 1.7 kilotonnes (kt) nuclear warhead at different altitudes between 200 and 540 km. The use of a nuclear warhead for this purpose converts the missile into an electronic weapon; the electromagnetic pulse produced from the detonation can disable satellites (the radiation damages electronic components and solar cells). The first true ASAT test (Starfish Prime) in which satellites were destroyed was conducted by the US in July 1962, and consisted of the detonation of a 1.4 megaton nuclear warhead at an altitude of about 400 km to test the effects of the electromagnetic pulse of the nuclear explosion. The effects of this test were devastating, destroying three satellites (two American and one British) and damaging another three (two American and one Soviet); in other words, the explosion destroyed or damaged about a third of all satellites in orbit at the time. The Soviet Union conducted four high-altitude nuclear tests in 1961 and 1962: in October 1961 two nuclear tests of 1.2 kt each at altitudes of 150 and 300 km, and in October 1962 two additional nuclear explosions of 200 and 300 kt, at similar altitudes (Johnston 2009).
9. Four different orbits are used by satellites: Low Earth Orbit (LEO, between 100-2,000 km) by communications and Earth observation satellites, Medium Earth Orbit (MEO, between 2,000 and 35,786 km) for navigation and positioning (GPS, GLONASS, Galileo and BeiDou), Geostationary Earth Orbit (GEO) at 35,786 km (communication/broadcast satellites), and High Earth Orbit (HEO>35,786 km). The most populated orbits are LEO and GEO.
10. A large number of tests were carried out during the period from 1962 to 1970, although information about the characteristics and results of the tests is very limited.
11. This was the ASM-135, based on the AGM-69 SRAM with an Altair upper stage. The system was carried on a modified F-15 Eagle (Grego 2012).
12. This is the tracked debris from this test using the technology of the 1980s. This technology has been improving over time, and, therefore, the estimations of debris for the different tests are not directly comparable.

13. It is known that in the 1980s the Soviet Union developed a DA-ASAT missile to be launched from an aircraft (the Kontakt launched from a modified MiG-31), like the ASM-135 of the US (Kommel and Weeden 2020).
14. Additionally, the anti-aircraft S-400 and S-500 systems have ASAT capabilities, as they have the dual purpose of surface-to-air anti-ballistic missiles and DA-ASAT weapons (with an operational range of up to 600 km).
15. At the beginning of the twenty-first century China developed the SC-19 anti-ballistic missile as an ASAT weapon, and it conducted a series of tests during the 2000s. During the 2010s, China developed a new ASAT missile, the Dong-Neng (DN-2 and DN-3), which it tested several times during the decade.
16. As a matter of fact, on 22 January 2013 a small Russian satellite (BLITS) was destroyed by debris from the Feng-Yun 1C (NASA 2013).
17. This is the case for the X-20 Dyna-Soar Project, which started in 1957, or the MOL Project of 1963 for deployment of manned battle-stations in space by the US, or the Almaz project by the Soviet Union (Pfrang and Weeden 2020c). Whereas the US cancelled both programs, the Soviet Union built and put into orbit several Almaz battle-stations (Salyut 2 failed shortly after achieving orbit, but Salyut 3 and Salyut 5 were successful), although the project was cancelled in 1978. Salyut 3, at least, was armed with an aircraft cannon, and the plan was to equip it with a carbon dioxide laser.
18. Space Command said a Russian satellite, Cosmos 2543, 'operated in abnormally close proximity to a US government satellite in low-earth orbit before it manoeuvred away and over to another Russian satellite, where it released another object in proximity to the Russia target satellite. This test is inconsistent with the intended purpose of the satellite as an inspector system, as described by Russia.'.
19. According to Raytheon Technologies Corporation, the EKV and SM-3 ASAT weapon systems have a combined record of 40 successful interceptions in space.
20. This vehicle has been in orbit six times from April 2010, increasing the duration of its missions from 224 days for the first to 780 days for the last (Weeden 2020b; Pfrang and Weeden 2020g).
21. According to Grego (2012), the US has developed the MIRACL ground-based laser as an ASAT weapon. In 1997 a test by the US using the MIRACL system damaged a satellite at an altitude of 420 km. The Soviet Union/Russia has developed several types of ASAT energy weapons. During the 1980s the Soviet Union developed an orbital weapon platform (a space battle-station), the Polyus, armed with a carbon dioxide laser. This battle-station was launched in May 1987 but failed to reach orbit. It used the same laser weapon as had previously been developed for the Beriev A-60 aircraft. Apart from ground-based laser weapons, another strategy has been the development of airborne lasers, using the Boeing YAL-1 or the Beriev A-60 aircraft by the Soviet Union. More recently, in 2003, Russia started developing a new airborne laser, the Sokol-Eschelon, also based on the Beriev A-60 aircraft (Grego 2012). Little information is available about the Chinese ASAT energy weapon program, except that some spacecraft have been illuminated by Chinese lasers.
22. In December, 2011 a U.S. surveillance drone was captured by Iran using this technique (Ruckle 2019).
23. The dynamics of the number of objects in orbit depends on several factors. Launches, collisions, explosions, and ASAT tests contribute positively to the amount of debris. By contrast, atmospheric drag and operational de-orbiting activities contribute negatively, reducing the amount of debris. The decline in the total number of objects in orbit during the years 1989 and 1990 is explained by a larger number of (both intentionally and naturally) de-orbited objects than the new objects in orbit.
24. This method for calculating the risk of collision considers an average size of space objects to estimate the probability of collision of two objects. For an alternative way of modelling the probability of collision, see Letizia et al. (2017).
25. Once the calibrated model is solved numerically for the optimal quantity of satellites and launches, we simulate a shock in the dynamic equation for the stock of orbital debris. The equilibrium of the model (the steady state) is defined as the solution for which the number of launches is those required for replacing destroyed or end-life satellites, such as the number of satellites in orbit remains constant. For simulating an AD-ASAT test, the shock takes the value of the number of fragments produced by the test. Given the shock we obtain the so-called impulse-response functions for the key variables of the model, indicating how these variables respond to the shock over time once the shock takes place. The impulse-response functions are represented in terms of percentage deviations of the variables with respect to their initial equilibrium value.
26. https://www.ucsusa.org/resources/satellite-database. Data for May 1, 2022. The UCS Satellite Database contains details on 5,465 satellites in orbit, including their country of origin, purpose, and other operational details.

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