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Russian Nuclear Weapons in Space?

Potential Destructive Consequences in Space, Escalation on Earth, and Damage to Arms Control

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According to the US government, the Russian government is developing a programme to arm some of its satellites with nuclear warheads. Should the Kremlin acquire this capability, it could destroy key parts of the civilian satellite infrastructure by detonating a single nuclear weapon in low Earth orbit. Important US military satellites are also located in space. The use of Russian nuclear weapons there could severely weaken the US military and potentially trigger a military escalation on Earth. The deployment of a nuclear warhead in space would constitute a violation of the Outer Space Treaty. The development of this capability appears to align with Russia's strategic approach of undermining the established international order and engaging in high-risk actions to extract concessions from the West, particularly in the context of Ukraine. The Kremlin is also attempting to incorporate the increasingly militarised domain of space into this strategy by using non-nuclear anti-satellite weapons. Europe must be prepared to address this ongoing challenge.

Western countries and societies are becoming increasingly dependent on space-based technology. These communities rely on commercial services that utilise satellite-based communication systems. The war in Ukraine has illustrated the pivotal role that space-based technology plays in modern warfare, with satellites being instrumental in reconnaissance missions and the coordination of unmanned aerial vehicles. As the West's dependency on this technology grows, so does its vulnerability. This threat is currently accelerating as a result of the investments by Russia and China in anti-satellite weaponry. Until now, these weapons have only consisted of conventional arms. Will they soon be nuclear?

Moscow's plans: What do we know?

There is general information available on Russia's anti-satellite weapons, and some details have now also emerged about the arsenal's nuclear aspect.

Cosmos 2553, a Russian satellite launched in early February 2022, is at the centre of attention. It immediately roused the interest of the US Armed Forces due to its loca-

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tion in an otherwise unused area of space that is typically reserved for decommissioned satellites. Russia claims that its decision to utilise this orbit is purely scientific: The aim is to test the resilience of materials and electronic components to higher levels of radiation. However, the US government does not consider this explanation to be credible, as the level of radiation in Cosmos 2553's orbit is very high, yet not high enough to justify the endurance tests described by Moscow.

In addition to the existence of Cosmos 2553, it appears certain that Russia has a nuclear anti-satellite programme. American intelligence services have been monitoring it with concern for almost a decade. The US government believes that, in the foreseeable future, Moscow could arm one or more satellites with a nuclear warhead.

However, according to the current consensus, Cosmos 2553 is not an active, "live" anti-satellite weapon. Therefore, there is no immediate threat. Nevertheless, US media outlets, citing government sources, claim that the Russian satellite is currently equipped with a dummy warhead. If this were true, it would provide further strong evidence against the Russian government's scientific explanation. Beyond these relative certainties about Cosmos 2553 and Russia's plans, three questions remain unanswered.

Firstly, it is unclear which area of space would be targeted by a Russian nuclear-armed satellite. There are three main orbits: low Earth orbit (LEO) extends from 100 to 2,000 km above Earth's surface (see Figure 1). It is home to almost all commercial satellites and more than 90 per cent of all satellites in space. Cosmos 2553 orbits the Earth at an altitude of 2,000 km. Above LEO is the medium Earth orbit (MEO), which extends up to an altitude of approximately 36,000 km. There are far fewer satellites here, but they include core capabilities such as GPS, the European Galileo satellites, and the Russian navigation system GLONASS. The highest region is geostationary Earth orbit (GEO), which extends beyond 36,000 km. GEO is home to weather and TV satellites, as well as strategic assets such as military communications satellites, command and control capabilities, and early warning systems for missile attacks.

The number and type of satellites affected by a nuclear explosion in space would therefore depend on their orbit. Detonating a nuclear weapon in LEO would affect the largest number of satellites and disrupt space-based capabilities across the board. A nuclear explosion in MEO would affect navigation systems that are also used for military purposes. The "assets" in GEO are crucial for strategic deterrence.

Secondly, the payload of a future nuclear-armed satellite cannot be identified from the outside until it is detonated. Although information from other sources is obtainable, it cannot be visually verified.

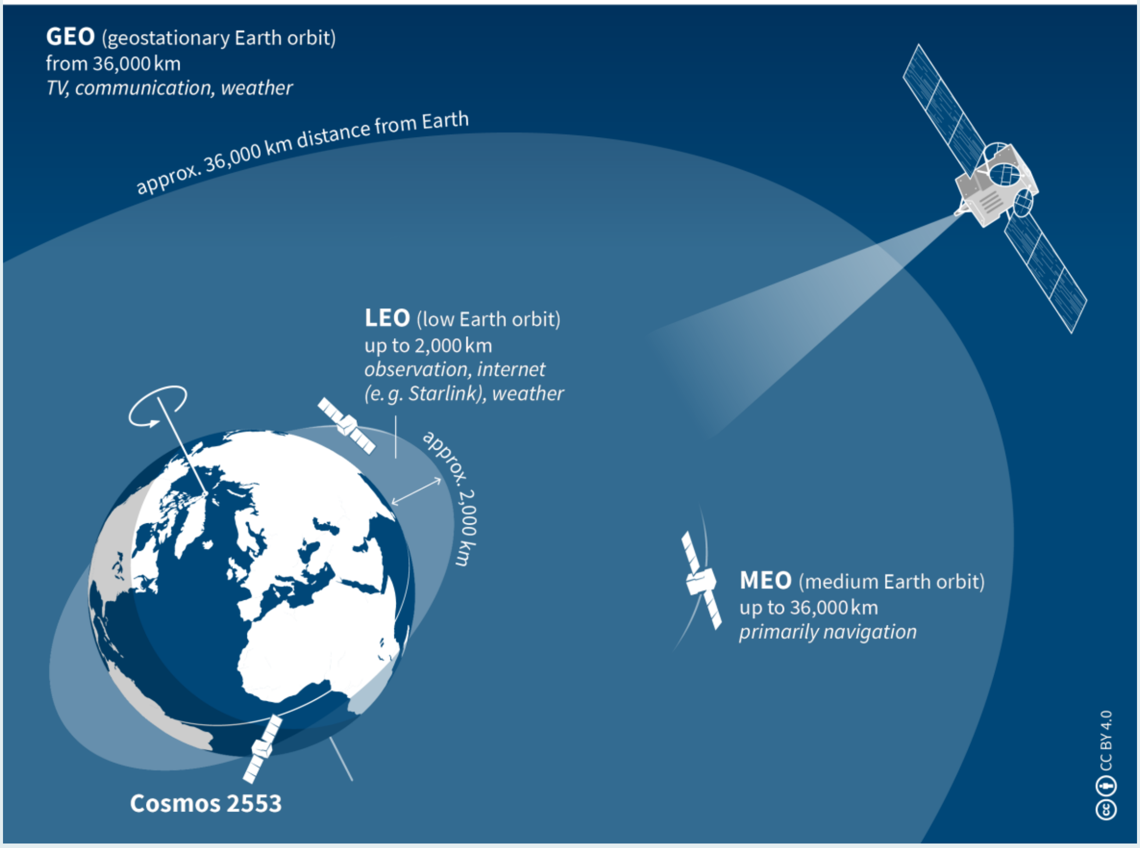
Thirdly, the strategic implications of Moscow's work to date on arming satellites with nuclear weapons are unclear. Is Russia merely seeking to retain the option of placing a nuclear-armed satellite in space at a later date if necessary (in which case it remains unclear whether it would actually be deployed)? Or is this an established weapons programme and the deployment is inevitable? If so, the satellite would be one option among many anti-satellite weapons at Vladimir Putin's disposal.

A variety of anti-satellite weapons

Taking action against satellites with the intent to destroy or disable them is not a new practice by states. The American "Bold Orion" test series was the first to demonstrate the ability to intercept satellites with air-launched missiles. It began in May 1958, just a few months after the Soviet Union launched Sputnik 1 in October 1957, which marked the beginning of the satellite age. Nowadays, anti-satellite measures such as "*jamming and spoofing*" satellite signals are a daily occurrence. For example, Russia has been jamming GPS signals in eastern Ukraine since 2014. These examples illustrate the wide range of anti-satellite weapons available today, some of which have already been deployed.

Figure 1

Three main Earth orbits



At one end of the spectrum are anti-satellite weapons with relatively mild effects, such as the temporary disruption of a satellite's signals. However, states such as Russia use them in wartime to limit the military capabilities of their opponents, and outside of wartime to demonstrate their rivals' vulnerabilities and to identify weak points in preparation for a potential conflict.

Weapons with greater impact, however, can cause permanent damage to satellites or even destroy them physically. The development of such capabilities in Russia is likely part of an overall strategy of blackmail to influence Western actions by demonstrating that the Kremlin's destructive potential has a global reach and suggesting that Moscow may be prepared to take such risky and reckless action.

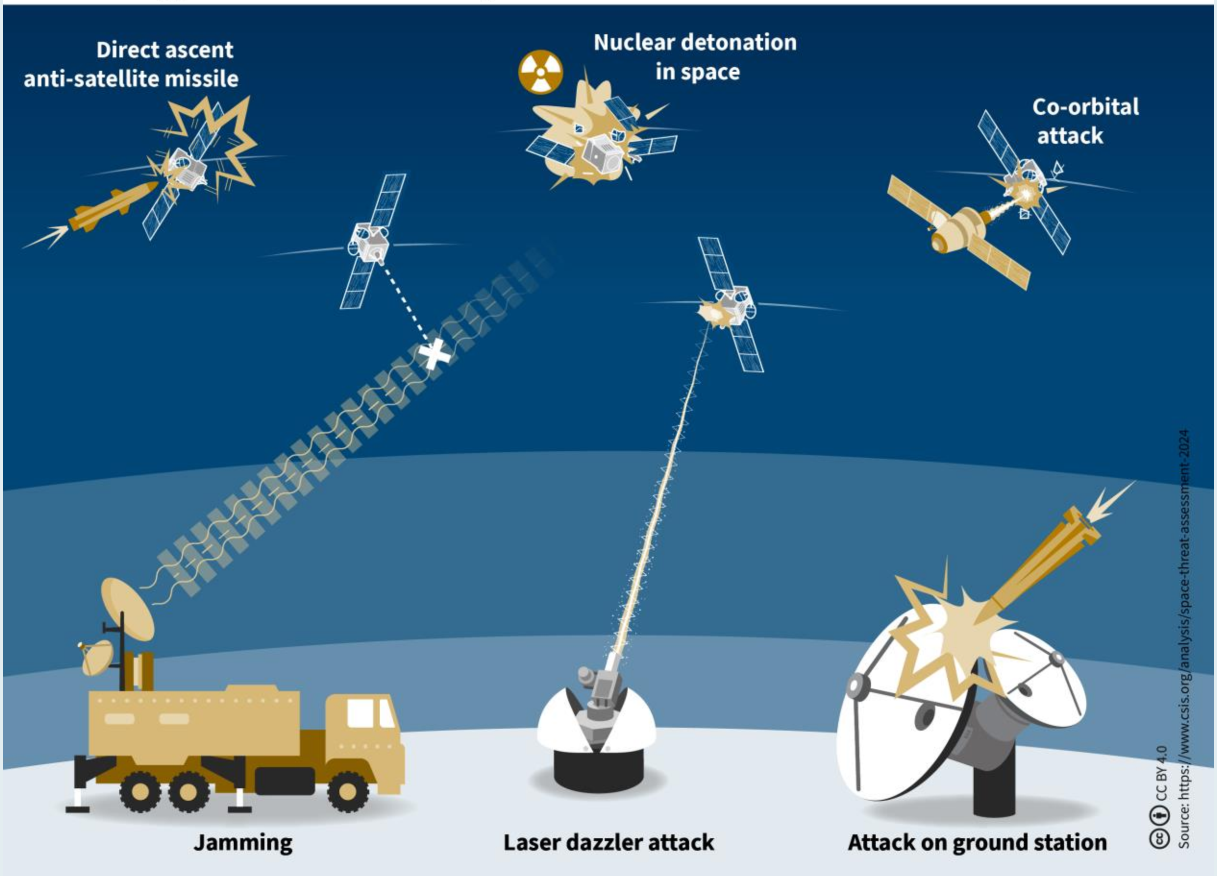
Beyond their effectiveness, anti-satellite weapons differ in terms of what they target: They can attack satellites in space, ground stations on Earth, or interfere with signals sent between these two points (see Figure 2).

Anti-satellite weapons can be roughly divided into four groups: electronic measures, cyber attacks, kinetic weapons, and non-kinetic weapons. Electronic measures include the aforementioned systems for jamming and spoofing satellite signals. Signal jamming temporarily prevents a GPS or other signal from reaching the receiver. In the case of spoofing, false signals are temporarily transmitted. Frequent spoofing by Russia in 2024 endangered civil aviation over Estonia.

Satellite systems are also being attacked using cyber tools. As early as 2007 and 2008, the ground station for American satellites located in Svalbard, Norway, was hacked. At the time, the attackers would even have been capable of manoeuvring the US satellites, but they chose not to do so. This shows that it does not take a spacefaring nation

Figure 2

Different types of anti-satellite weapons and measures



to cause harm in space. A cyber attack is enough to target satellite systems.

The category of kinetic anti-satellite weapons includes systems in space and on Earth. Attacks on ground stations can disable a satellite system, for example through air strikes or sabotage.

Russia has conducted tests that indicate a kinetic co-orbital function: It has fired projectiles at a high speed in space. Co-orbital weapons — that is, weapons stationed in space — can also include satellites that perform *"rendezvous and proximity manoeuvres"* with other satellites and could be used for hostile purposes. Satellites could be attacked at close range or even grabbed with gripping arms and placed in a new orbit. China proved this in 2021 using one of its own decommissioned satellites.

The most well-known kinetic capability is "direct ascent" anti-satellite weapons. These involve launching missiles from the ground to kinetically destroy a satellite. So far, the United States, Russia, China, and India have demonstrated this capability — but only against their own decommissioned satellites. These are tests of military deterrence capabilities: a form of signalling to rivals during tense situations. For example, China destroyed a weather satellite in 2007 amid tensions with Taiwan. The United States responded by shooting down one of its own defunct satellites in 2008. In late 2021, shortly before its invasion of Ukraine, Russia shot down a reconnaissance satellite.

Finally, non-kinetic weapons include capabilities in space and on Earth, such as laser weapons designed to interfere with the optical sensors of reconnaissance and Earth observation satellites. Very low levels of laser energy are sufficient to dazzle the sensors and disrupt satellite operations.

More powerful lasers can physically damage the sensors and permanently disable them. China almost certainly possesses such weapons, Russia claims to have them, and the United States has met all of the prerequisites for developing these laser systems.

Non-kinetic co-orbital weapons could interfere with other satellites by using chemicals, eavesdropping on them, or photographing them in order to determine what the satellite is being used for. A nuclear detonation in space would also be considered a non-kinetic weapon.

Atomic explosions in space can destroy or impair not just individual satellites, but large numbers of them in a single strike. Such a detonation can be achieved by equipping a satellite with a nuclear warhead, which can also be launched into space at the front end of a missile. All nine nuclear-armed states have this capability, regardless of whether they are spacefaring nations: They possess intercontinental or at least medium-range missiles that can be equipped with nuclear warheads. These could enter LEO on their ballistic trajectory and detonate a nuclear warhead there before returning to Earth. The Soviet Union and the United States already conducted testing in the 1950s and 1960s.

What effects do nuclear weapons have in space?

If a nuclear weapon were detonated in space, it would have three effects. The consequences would depend on the location of the detonation.

First, an atomic explosion would result in countless fragments of debris — or space junk — due to a massive release of gamma particles (gamma blasts), which would destroy satellites within a radius of about 80 km. If these fragments were to hit satellites further away, they would also be damaged, thus creating more debris. Since satellites move at very high speeds in space, even the smallest fragments could cause significant destruction upon collision. Especially in the densely populated LEO, the number of these explosion-induced debris fragments — essentially transformed into projectiles — would be enormous.

In addition, a nuclear explosion in space would significantly increase radiation levels. The amount would depend on the explosive power of the nuclear weapon. A study by the US government suggests that the radiation from a lower-yield explosion (10—20 kilotons) in LEO would immediately affect 5 to 10 per cent of all satellites in space. Due to Earth's magnetic field, the resulting surge in radiation would not subside quickly — it could persist for months, if not years. Even satellites not damaged immediately by the nuclear detonation would not remain operational for long. This is because a satellite's onboard electronics would require more energy due to the radiation. As a result, the satellite's altitude control, the electronic components themselves, and the communication link would gradually fail.

Finally, a nuclear explosion in space would generate an electromagnetic pulse (EMP). This would disrupt the onboard electronics of satellites. An EMP could also have severe effects on Earth if the explosion occurred in LEO. Although human lives would not be directly at risk, widespread power outages and severe long-term damage to electrical grids could be expected — leading to cascading consequences, such as serious disruptions to medical care.

Options for resilience are limited

The consequences of these physical effects in space for Earth also depend on whether the passive protection of satellites against the effects of nuclear explosions is possible. However, there are significant obstacles to implementing resilience-enhancing measures.

It is technically possible to protect satellites from radiation and an EMP. Special coatings can "harden" the materials against these two effects. All satellites are somewhat hardened against radiation, as space is a radiation-intensive environment. The level of natural radiation depends on the specific orbit. Since radiation is least intense in LEO and satellites generally stay in this environment for a relatively short time (typically five to seven years), satellites in this orbit are currently the least shielded against radiation. However, the level of radiation resulting from a nuclear explosion — which would remain high for a long time in space — would far exceed the current resilience capacities of most satellites in LEO. Additional radiation hardening would increase the size — especially the weight — and consequently the price of the commissioned satellite. This makes it unattractive as a preventive measure, especially for commercial service providers.

Commercial satellites are not protected against an EMP at all. This is primarily a cost issue, as EMP hardening is estimated to increase the total price of a satellite by 5 to 10 per cent — an enormous margin in a highly competitive market. For strategic assets, however, such cost differences are insignificant. These systems are expected to remain operational under all circumstances. For this reason, all American military satellites, for example, are EMP-hardened and protected against radiation.

Although developing a satellite's resilience against radiation and EMPs is technically feasible — though expensive — a lasting and effective defence against debris remains impossible. The only apparent way to avoid its effects is if the debris is located in an entirely different orbit. If debris spreads within the same orbit, the chances of survival increase only if the gamma blast from the explosion destroys relatively few satellites. This scenario is conceivable in MEO and GEO, but almost impossible in LEO. For this reason, the US government assumes that LEO would be unusable for a year following a nuclear explosion in the same orbit. However, experts consider even that to be an optimistic estimate.

Risk of escalation depends on context

Since passive protection is so limited, a Russian nuclear explosion in space could cause such widespread destruction that the United States might feel compelled to retaliate. Depending on the nature of the US response, there could also be a risk of further escalation on Earth.

Virtually nothing is publicly known about how the US government would respond to a Russian nuclear strike in space. However, the American response would likely depend heavily on the extent of destruction caused by Russia — both in quantitative and qualitative terms.

Severe damage would be especially likely if Moscow were to detonate a nuclear weapon in LEO. Since this region of space is particularly densely populated, the destruction caused by debris would likely be extremely high. Radiation damage would also be greater in LEO than in other orbits, as the many commercial systems there are scarcely hardened. In addition, harmful EMP effects could also occur on Earth in the event of a nuclear detonation in this near-Earth orbit.

In qualitative terms, the United States would face devastating consequences from a Russian nuclear strike in space if key military satellites were affected. Traditionally, this concerns the strategic "assets" of the United States in GEO. The constellation of GPS satellites in MEO is equally important. However, military-related satellite systems have also been stationed in LEO for some time now. These include *Starshield*, which is the military counterpart to the leading commercial satellite internet provider, *Starlink*. The US Department of Defence is also expanding early warning capabilities in LEO to counter the increasingly complex threat posed by new types of missiles, such as hypersonic glide vehicles.

Washington's response to a nuclear strike in space would depend on the context of the individual case: the trajectory of the crisis as well as where the attack is located on the axes of quantitative and qualitative damage. Non-military retaliation by the United States would be most plausible if a nuclear explosion in the sparsely populated MEO or at the outer edge of LEO destroyed only a small number of commercial satellites and — in the absence of an EMP on Earth — did not cause any fatalities. Presumably, painful financial and trade sanctions and harsh cyber strikes would be the means of choice for Washington in the event of such manageable "purely economic" damage.

A deliberately limited US response would also be expected if a Russian nuclear explosion were to disable only a few non-critical US military systems. In such a case, it would be logical for the US government — on grounds of proportionality — to disable a few Russian military satellites, for example using non-kinetic means. A comparable strike against Russian military infrastructure on Earth might also be considered. This response by the United States would also focus on avoiding further military escalation. However, the extent of the damage caused by a Russian nuclear explosion to commercial and, above all, military space systems would increase the pressure on Washington to strike back hard.

US retaliation would likely take a very different form if a Russian nuclear strike were to disable space-based assets that are vital to US national security. A severe military response on Earth could be expected if American military satellites were damaged to the extent that the United States even partially lost the ability to: 1) conduct conventional wars overseas, 2) issue early warnings of an intercontinental nuclear strike against US territory, or 3) retaliate against such a nuclear attack. In this case, even the limited use of US nuclear weapons could not be ruled out. The Trump administration's 2018 *"Nuclear Posture Review"*, for instance, explicitly reserved the right to respond with nuclear retaliation to strategic attacks on the space-based *"command and control, or warning and attack assessment capabilities"* of US nuclear forces. Scenarios of this magnitude naturally carry a high risk of further escalation.

Arms control at risk

Damage to the arms control architecture would occur before any destruction in space or escalation on Earth takes place.

The first aspect to be affected would be the 1967 Outer Space Treaty, which serves as the cornerstone of all arms control efforts in space, as it prohibits the stationing of nuclear weapons in outer space. The mere placement of a Russian satellite equipped with a nuclear warhead in space would violate this arms control treaty — regardless of whether the warhead is ever detonated.

The 1963 Partial Test Ban Treaty expressly prohibits conducting nuclear tests in outer space, in the atmosphere, and underwater. A violation of this agreement would only occur if Moscow were to detonate a nuclear warhead in space — not before.

Russia is a party to both arms control treaties. The Soviet Union helped negotiate — and soon after ratified — the agreements in the 1960s. However, in 2024 the Kremlin rejected the Biden administration's efforts to reaffirm the Outer Space Treaty within the United Nations (UN) framework, which would have strengthened the prohibition on stationing nuclear weapons in space. At the same time, Russia denies any intention to pursue such deployments. Yet, its explanation that Cosmos 2553 is strictly for civilian purposes is entirely implausible. Through its actions, Moscow is undermining the Outer Space Treaty. As in other areas of arms control, the Russian government is once again increasing pressure on the West.

Policy recommendations

Germany can take four steps to help reduce the likelihood of Russian nuclear weapons in space and better prepare for violent conflicts with Russia in space.

First, Germany should provide more actively diplomatic support for strengthening the Outer Space Treaty. Russia blocked the UN initiative by the United States and Japan to reaffirm the treaty in the Security

Council with China's help. However, there are indications that China — as the second strongest space power after the United States — is interested in a broad diplomatic rejection of Russian nuclear weapons in space. Beyond the symbolically charged Security Council vote, there should be scope for achieving a cross-bloc condemnation of nuclear-armed satellites with China's consent, for example within the G20 framework or at EU-China summits. This would make a violation of nuclear norms in space politically less attractive for Moscow.

Second, Germany should strive to impose costs on Russia not only in terms of higher diplomatic costs, but also directly in space if the Kremlin destroys Western and German infrastructure there. Options include non-kinetic measures against Russian satellites such as jamming or spoofing signals, or dazzling them with laser beams. The development of such (moderate) retaliatory capabilities has begun in Germany and should continue in order for it to make its own contribution towards nuclear deterrence in space.

Third, Berlin should go beyond such "deterrence by punishment" options and build up "deterrence by denial" capabilities in space: If Russian attacks in space become less likely to succeed, this should also deter Moscow from such attacks. To this end, the German Armed Forces are developing a "bodyguard satellite" that will accompany high-value German satellites and physically block the path of approaching enemy satellites. Better passive protection against cyber attacks on the ground would be another useful measure. In addition, the probability of Russian attacks succeeding decreases with the increasing redundancy of Germany's own capabilities in space. This can be achieved through a large number and diverse range of systems. Germany still has a long way to go in this regard. However, the current direction — towards large German and European constellations of satellites — is the right one.

Fourth, the Federal Republic should invest more in a comprehensive situational awareness of space, also in collaboration with its closest partners. If attempts by adversarial states to disrupt or damage satellites cannot be observed or proven, an aggressor can plausibly deny their actions. This undermines deterrence through the threat of retaliatory countermeasures. Defence also relies on reliable intelligence. Activities in space must be traceable. Europe's current heavy reliance on the United States in this regard should be reduced.

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