9

Conclusion

Where To from Here?

As is evident throughout this book, the global governance regime for Space is grounded in six decades of co-operation between the Soviet Union and then Russia on the one hand, and the United States and its allies on the other. The Apollo–Soyuz 'handshake in Space',[1] planned during the Vietnam War and carried out shortly after the fall of Saigon, reminds us of the depths of this co-operation. China and India's rapid rise as spacefaring states has occurred within this governance regime.

But continued co-operation is not guaranteed. Significant divisions exist, such as those between the Artemis Program and the Russia–China International Lunar Research Station.[2] The US Congress's ban on direct co-operation between NASA and the China National Space Administration (CNSA), which is known as the 'Wolf Amendment' and dates to 2011, may be helping this division to grow.[3] Moreover, as China, India and Russia form stronger ties in Space, it is reasonable to question whether the long-stable Space governance regime will fracture into two parallel systems, one led by the United States and the other by Russia and China.

The Ukraine War has the potential to be the bifurcation point.

Russia launched a full-scale invasion of Ukraine on 24 February 2022, sending tanks, artillery and some 200,000 soldiers into the country. As Ukrainians fought back, the United States and its allies adopted deep-reaching sanctions. Co-operation between Russia and Western states stopped abruptly, including in the United Nations Security Council where

[1] Anatoly Antonov, 'With the Apollo–Soyuz handshake in space, the Cold War thawed a little', *Smithsonian Magazine* (15 July 2020), online: www.smithsonianmag.com/air-space-magazine/apollo-soyuz-cold-war-thawed-little-180975321.

[2] Jeff Foust, 'Russia continues discussions with China on lunar exploration cooperation', *SpaceNews* (4 April 2022), online: spacenews.com/russia-continues-discussions-with-china-on-lunar-exploration-cooperation.

[3] Jeff Foust, 'Defanging the Wolf Amendment', *Space Review* (3 June 2019), online: www.thespacereview.com/article/3725/1.

Russia holds a veto. Vladimir Putin went so far as to threaten the use of nuclear weapons if third states interfered in his 'special military operation'.[4]

As a result of these actions, some elements of international Space co-operation broke down immediately. Russia refused to launch a Soyuz rocket that was already on the pad in Kazakhstan with a payload of satellites owned by the British–Indian company OneWeb.[5] It also cancelled all Soyuz launches from French Guiana, which had for years been conducted in partnership with the French company Arianespace.[6] Then, the European Space Agency (ESA) suspended plans to launch the ExoMars lander on a Russian rocket in September 2022[7] and stopped collaborating with Russia on the Lunar 25, 26 and 27 landers.[8] At the United Nations, Russian diplomats postponed the first substantive session of a new Open Ended Working Group on Reducing Space Threats through Norms, Rules and Principles of Responsible Behaviours by raising a 'litany of procedural complaints'.[9]

Nevertheless, despite these developments, other more established forms of Space co-operation continued, including on the International Space Station (ISS) and with Cospas-Sarsat.

[4] According to a translation of Putin's speech on 24 February 2022, published by the *New York Times*, the Russian president said, 'I would now like to say something very important for those who may be tempted to interfere in these developments from the outside. No matter who tries to stand in our way or all the more so create threats for our country and our people, they must know that Russia will respond immediately, and the consequences will be such as you have never seen in your entire history.' Max Fisher, 'Putin's case for war, annotated', *New York Times* (24 February 2022), online: www.nytimes.com/2022/02/24/world/europe/putin-ukraine-speech.html.

[5] Joey Roulette, 'Russia's isolation on Earth moves up into space' *New York Times* (3 March 2022), online: www.nytimes.com/2022/03/03/science/russia-oneweb-launch.html.

[6] Jeff Foust, 'Russia halts Soyuz launches from French Guiana', *SpaceNews* (26 February 2022), online: spacenews.com/russia-halts-soyuz-launches-from-french-guiana.

[7] Tereza Pultarova, 'European Space Agency suspends Mars rover launch on Russian rocket', *Space.com* (17 March 2022), online: www.space.com/europe-suspends-exomars-mars-rover-launch-russia.

[8] Tereza Pultarova, 'Europe halts moon exploration partnership with Russia, looks to replace Ukraine-built rocket engines', *Space.com* (13 April 2022), online: www.space.com/europe-moon-pertnership-russia-ukraine-rocket-engines.

[9] Theresa Hitchens, 'No love from Russia for UN military space norms meeting', *Breaking Defense* (9 February 2022), online: breakingdefense.com/2022/02/no-love-from-russia-for-un-military-space-norms-meeting.

9.1 The International Space Station

On 18 March 2022, three Russian cosmonauts arrived on the ISS wearing bright yellow flight suits with blue trim,[10] causing widespread speculation on social media that they were protesting the invasion of Ukraine. Both the Russian space agency (Roscosmos) and the cosmonauts themselves denied the colours were chosen for this reason, and a US astronaut, Mark Vande Hei , also on board, later confirmed their account.[11] But the idea that the suits were a protest still appeals to many, as the ISS is a powerful symbol of peace.

The most expensive structure ever built by humanity, the ISS has been continuously inhabited for more than two decades by Russian cosmonauts and Western astronauts. If you know where and when to look,[12] you can see the ISS sail across the sky, even in light-polluted cities. This beacon of light is a reminder of what humanity can do when it chooses peace and co-operation over conflict and division. Indeed, the ISS was conceived largely as a peace mission.

Russia's involvement in the ISS helped to prevent the proliferation of expertise and technology to terrorists and rogue states following the dissolution of the Soviet Union, while giving Western states access to Russian expertise in long-duration spaceflight as well as reliable Soyuz rockets for resupply and crew rotations. Indeed, for nine years after the Space Shuttle program was shut down in 2011, Soyuz was the only way to access the ISS, including for American astronauts. Even during the Crimean crisis in 2014, the West and Russia co-operated on the ISS.

But the 2022 Ukraine War appears to be different, and it is not immediately clear whether Russian–Western relations in Space will remain as resilient as before.

When US president Joe Biden announced the first round of new sanctions against Russia on 24 February 2022, he emphasised that a ban

[10] Kenneth Chang, 'Russia's astronauts enter the space station in yellow and blue flight suits', *New York Times* (18 March 2022), online: www.nytimes.com/2022/03/18/science/russian-astronauts-yellow-blue-flight-suits-ukraine.html.

[11] Christian Davenport, 'NASA astronaut: Russians were "blindsided" by reaction to yellow suits', *Washington Post* (5 April 2022), online: www.washingtonpost.com/technology/2022/04/05/mark-vande-hei-russia-ukraine-yellow-suits.

[12] We recommend NASA's 'Spot the Station' webpage where you can enter your location to see upcoming viewing opportunities: spotthestation.nasa.gov/home.cfm.

on high-tech exports would 'degrade their aerospace industry, including their space program'.[13] Dmitry Rogozin, the director general of Roscosmos, responded by pointing out that the ISS is dependent on propulsion from Russian spacecraft, with regular boosts countering the effect of gas drag and preventing an atmospheric re-entry. 'If you block cooperation with us, who will save the ISS from an uncontrolled de-orbit and fall into the United States or Europe?' Rogozin wrote on Twitter.[14]

While this tweet was written in Rogozin's typical bombastic style, it was not without substance. Should Russia (wilfully or otherwise) stop providing regular boosts, the other ISS partner states would have difficulty keeping the station in orbit. At a minimum, new equipment and procedures would need to be developed at breakneck speeds to prevent an uncontrolled re-entry.

All the ISS partner states, especially Russia, have invested too much money, effort and national prestige into the project to allow it to fail. Russian propaganda has suggested that the Russian modules might be detached, presumably forming their own Space station,[15] but Roscosmos would then have to replace electrical power currently provided by the rest of the ISS. This would probably require a new module – one that would take years to build and launch. Joining the Russian modules to China's new Tiangong Space station is not an option, either, because of a ten-degree difference in the inclination of the orbits.

With these realities in mind, on 25 February 2022 – just one day after Rogozin's threatening tweet – Russia quietly conducted a pre-scheduled boost: to raise the orbit of the ISS, not crash it into the ocean.[16] The following week, Vande Hei made a pre-scheduled return to Earth in a

[13] White House, 'Remarks by President Biden on Russia's unprovoked and unjustified attack on Ukraine' (24 February 2022), online: www.whitehouse.gov/briefing-room/speeches-remarks/2022/02/24/remarks-by-president-biden-on-russias-unprovoked-and-unjustified-attack-on-ukraine.

[14] Steve Gorman, 'NASA shrugs off Roscosmos leader's rant over U.S. sanctions and space station', *Reuters* (25 February 2022), online: www.reuters.com/world/europe/nasa-shrugs-off-roscosmos-leaders-rant-over-us-sanctions-space-station-2022-02-26.

[15] India Today Web Desk, 'Russia detaches from International Space Station in propaganda video', *India Today* (6 March 2022), online: www.indiatoday.in/world/russia-ukraine-war/story/russia-detaches-international-space-station-propaganda-video-watch-1921266-2022-03-06.

[16] Mark Garcia, 'Crew works robotics, spacesuits as station orbits higher for crew swap' (28 February 2022), *NASA Space Station*, online (blog): blogs.nasa.gov/spacestation/2022/02.

Soyuz capsule, landing in Kazakhstan, before being whisked off in a NASA aircraft back to the United States.[17]

Shortly after Vande Hei's return, Rogozin took to Twitter again, threatening to suspend ISS co-operation if Western sanctions are not lifted and stating that Roscosmos would decide on a date to end Russia's involvement.[18] While tweets from the director general of Roscosmos cannot be ignored, it should be recognised that, just before Vande Hei and two Russian cosmonauts returned to Earth, three additional cosmonauts – the ones with the yellow flight suits – joined the ISS crew.

It is difficult to overstate the depth of the rift caused by the Ukraine War, or the dangers associated with it. The ISS will eventually be decommissioned and safely de-orbited. Russia might try to make that day come sooner than the United States would like, but it does not yet have another clear and achievable plan for maintaining a Russian presence in Space. Eventually Russia and China might forge their own path forward in low Earth orbit (LEO), and perhaps on the Moon, but for now some co-operation between Russia and Western states continues in Space, and not just on the ISS.

9.2 Cospas-Sarsat

Around the globe, individuals venturing into the wilderness for work or recreation are encouraged to carry satellite search-and-rescue beacons, while most ships and airplanes are required to be equipped with such beacons by law. The beacons save literally thousands of lives each year by taking the 'search' out of search and rescue. But they are only able to do so because of a unique international organisation that was created during the Cold War.

The International Cospas-Sarsat Programme co-ordinates the detection and location of activated beacons and ensures that this information is promptly sent to the relevant authority responsible for search and rescue in the territory or maritime zone from which the distress signal is

[17] Chelsea Gohd, 'NASA astronaut Mark Vande Hei back on Earth after record-breaking mission', *Space.com* (31 March 2022), online: www.space.com/nasa-astronaut-mark-vande-hei-lands-earth-misses-wife.

[18] Emma Roth, 'Russia says it will suspend ISS cooperation unless sanctions are lifted', *The Verge* (4 April 2022), online: www.theverge.com/2022/4/2/23007575/russia-suspend-iss-cooperation-sanctions-lifted-ukraine-space-nasa.

received.[19] It uses a network of satellites that provide coverage of the entire planet, including five satellites in LEO polar orbits, 17 in geosynchronous orbit, and more than 50 in medium Earth orbit.[20] The instruments providing this service travel as secondary payloads on the satellites, which have other missions such as collecting meteorological data or providing global positioning signals. The satellites in the network are owned and operated by the United States, Russia, France, Canada, India, the European Union and EUMETSAT, the European Organisation for the Exploitation of Meteorological Satellites. Dozens of ground stations track the satellites and receive signals relayed by them, including at least one in China.[21] Information about distress signals and their locations is distributed to search-and-rescue centres in over 200 countries and territories – at no cost to the owners of the beacons or to the governments that conduct the rescues.

The International Cospas-Sarsat Programme was created by Canada, France, the United States and the Soviet Union in 1979.[22] The first rescue took place in 1982, just weeks after the first satellite in the system, COSPAS-1, was launched by the Soviet Union. In 1988, the four states decided to ground the system in a treaty: the International Cospas-Sarsat Programme Agreement.[23] Cospas-Sarsat is now a small but important international organisation with a permanent secretariat located in Montreal.[24] Since 1982, it has helped rescue at least 45,000 people by guiding more than 13,000 search-and-rescue missions worldwide.[25]

[19] See Daniel Levesque, ed., *The History and Experience of the International Cospas-Sarsat Programme for Search and Rescue* (Paris: International Astronautical Federation, 2016), online: https://cospas-sarsat.int/images/content/articles/Cospas-Sarsat-Report_ReducedSize_Jan-2019.pdf.

[20] 'Current space segment status and SAR payloads', *International Cospas-Sarsat Programme*, online: www.cospas-sarsat.int/en/current-space-segment-status-and-sar-payloads.

[21] Levesque, op. cit., Annex 3: 'States and organisations associated with or contributing to the Cospas-Sarsat programme'.

[22] Richard JH Barnes and Jennifer Clapp, 'Cospas-Sarsat: A quiet success story' (1995) 11:4 *Space Policy* 261 at 262–63; Levesque, op. cit.

[23] The International Cospas-Sarsat Programme Agreement, 1 July 1988, 1518 UNTS 209 (entered into force 30 August 1988).

[24] In 2005, Canada concluded a headquarters agreement for the organisation. See 'Arrangement between Canada, the Republic of France, the Russian Federation and the United States of America Regarding the Headquarters of the International Cospas-Sarsat Programme' (2005), *Government of Canada*, online: laws-lois.justice.gc.ca/eng/regulations/SOR-2005-112/page-2.html.

[25] See the website of the International Cospas-Sarsat Programme: www.cospas-sarsat.int/en.

The most interesting part of the Cospas-Sarsat story is that such a body was established during the Cold War – and that it survived through the extreme tensions of the early 1980s, which included the Soviet invasion of Afghanistan and US President Ronald Reagan's Strategic Defense Initiative ('Star Wars').[26] There are several possible explanations, the most obvious of which is that all of the partner states benefited from the programme, since combining all of their satellites and ground stations provided greater coverage and therefore faster notification of distress signals than would otherwise have been the case. These benefits were significant, since the four founding states have immense maritime zones, including around Canada and Russia's Arctic islands and France and the United States' overseas possessions, as well as global shipping interests. However, this explanation is not sufficient, as Richard Barnes and Jennifer Clapp have explained: 'Search and rescue satellite-aided tracking … was attractive to the Soviets because of their world-wide fishing fleet *and* because it provided them with an opportunity to demonstrate their space capability in a humanitarian application.'[27]

In other words, Cospas-Sarsat has succeeded because it implements the 'Good Samaritan' principle of assisting strangers in distress. As we explained in Chapter 6, this principle had already been set out in several major treaties, beginning with the International Convention for the Safety of Life at Sea,[28] which was prompted by the sinking of the *Titanic* in 1912 and adopted in 1914. As we write this several months into the Ukraine War, it seems that the humanitarian principle is just as powerful as it was before. Russia remains an active partner in Cospas-Sarsat, with four of its satellites listed as having fully operational search-and-rescue payloads on the programme's website in April 2022.[29] And yet, despite this co-operation, in Cospas-Sarsat and on the ISS, Space is also part of the Ukraine War.

[26] Barnes and Clapp, op. cit. at 266.
[27] Ibid. at 263 (emphasis added).
[28] International Convention for the Safety of Life at Sea, 1 November 1974, 1184 UNTS 278 (entered into force 25 May 1980).
[29] The four satellites are *Cospas-14*, *Electro-L No. 2*, *Electro-L No. 3*, and *Louch-5A*. One other Russian satellite is identified as 'available for ground segment testing' while three more are identified as 'under test'. See 'Current space segment status and SAR payloads', op. cit.

9.3 Space and the Ukraine War

Russia's anti-satellite (ASAT) weapon test of 15 November 2021 featured prominently in Chapters 7 and 8 of this book. Seen from a post-invasion perspective, the test was clearly meant as a warning to NATO states that Russia was willing to incur the increased risks from Space debris that would result from any use of kinetic ASAT weapons, including risks to its own cosmonauts in orbit. General David Thompson, the vice chief of Space operations for the US Space Force, admitted in April 2022 that this is also how the United States interprets the Russian test today: 'They [the Russians] were also making a very clear statement to us about their intention to threaten our capabilities.'[30] But the ASAT weapon test might not have been Russia's only threat against Space assets.

On 7 January 2022, one of the two subsea cables that connect the satellite ground station on the Svalbard archipelago to the Norwegian mainland suffered a disruption – at a location where the ocean depths drop sharply to about 2,700 metres.[31] After an investigation, the Norwegian police concluded that the disruption was no accident, stating, 'Preliminary investigations strengthen our hypothesis about human impact leading to the loss of communication in one of the cables', they said.

The satellite ground station on Svalbard is the largest such commercial facility in the world, with more than 100 receiving dishes. Located at 78 degrees north, it is perfectly located to download the vast amount of data produced by Earth-imaging satellites in polar orbit, with much of that imagery being used by NATO militaries. Since the second cable was not disrupted, the only loss was one of redundancy, which KSAT, the company that operates the station, was able to restore 11 days later. But there is little doubt that whoever used a submarine to interfere with the cable could have caused a complete disruption, had they wished to do so. It is reasonable to infer that the action was a warning, to Norway as well as other NATO states, that Russia could cut the ground station off at will. Given that this incident occurred just six weeks before the invasion of Ukraine, it should probably be considered as part of the Russian build-up to that action.

[30] Tom Costello, 'Russia is jamming U.S.-provided GPS signals in Ukraine, U.S. general says', *NBC News* (11 April 2022), online: www.nbc.com/nbc-nightly-news/video/russia-is-jamming-us-provided-gps-signals-in-ukraine-us-general-says/519685976.

[31] Atle Staalesen, '"Human activity" behind Svalbard cable disruption', *Barents Observer* (11 February 2022), online: thebarentsobserver.com/en/security/2022/02/unknown-human-activity-behind-svalbard-cable-disruption.

At the exact same time as Russia invaded Ukraine, early in the morning of 24 February 2022, a cyber attack was launched against the communications services provided to Ukraine by the US satellite company Viasat.[32] The attack, which exploited a misconfiguration in a VPN (virtual private network) appliance to obtain network access, targeted ground-based modems only. Ultimately, tens of thousands of them were forced off the network. Most of these modems were in Ukraine, but a 'substantial number' were in other parts of Europe.

A few days later, SpaceX sent hundreds of Starlink ground terminals to the Ukrainian government, in an apparent response to the cyber attack on Viasat, as well as to concerns about the vulnerability of ground-based cables. According to Elon Musk, as later corroborated by the director of electronic warfare for the Office of the US Secretary of Defense,[33] Russia proceeded to jam the terminals for hours at a time, until SpaceX responded with a software update that restored normal operability.[34] On 25 March 2022, Musk tweeted, 'Starlink, at least so far, has resisted all hacking & jamming attempts.'[35]

Russia, however, has been able to jam transmissions from the US military's global positioning system (GPS) satellites. In the interview he gave on 11 April 2022, General David Thompson said, 'Ukrainians may not be able to use GPS because there are jammers around that prevent them from receiving and using the signal effectively.'[36]

At the same time, Russia will, of course, be using its own satellites for global positioning, communications, situational awareness and signals intelligence in and around Ukraine. This is not entirely a bad thing, since having reliable information about what NATO forces are doing outside Ukraine could help to prevent the conflict from spreading. Satellites have long played a role in helping to prevent security dilemmas, which is why

[32] Viasat Corporate, 'KA-SAT network cyber attack overview' (30 March 2022), *Viasat Inc*, online (blog): www.viasat.com/about/newsroom/blog/ka-sat-network-cyber-attack-overview.

[33] Kate Duffy, 'A top Pentagon official said SpaceX Starlink rapidly fought off a Russian jamming attack in Ukraine', *Business Insider* (22 April 2022), online: www.businessinsider.com/spacex-starlink-pentagon-russian-jamming-attack-elon-musk-dave-tremper-2022-4.

[34] See Elon Musk, 'SpaceX reprioritized to cyber defense & overcoming signal jamming. Will cause slight delays to Starship & Starlink V2' (4 May 2022 at 23:59), *Twitter*, online: twitter.com/elonmusk/status/1499972826828259328.

[35] See Elon Musk, 'Starlink, at least so far, has resisted all hacking & jamming attempts' (25 March 2022 at 19:25), *Twitter*, online: twitter.com/elonmusk/status/1507505633259630599.

[36] Costello, op. cit.

some satellites are protected as 'national means of verification' in certain arms control treaties, as discussed in Chapter 7.

But there is a major difference between satellites used by Russia and those relied upon by Ukraine, in that many of the latter are commercially owned and operated. Viasat, SpaceX and literally dozens of other Western satellite companies are playing significant roles in the Ukraine War. In addition to aiding the Ukrainian military with communications and situational awareness, these companies are lifting the 'fog of war' by making high-resolution images accessible to everyone, and thus exposing indiscriminate attacks, atrocities against civilians, mass graves and Russian denials. More prominently than ever before, this development raises the question, discussed in Chapter 8, of the role of dual-use satellites in armed conflict. Are these commercial satellites now legitimate targets under international humanitarian law (*jus in bello*), which applies notwithstanding Russia's clear violation of the law governing the recourse to force (*jus ad bellum*)? And if commercial Space assets are targeted at any point – perhaps a Russian missile attack on a Western satellite, or the severing of both subsea cables to Svalbard – could this then trigger the right of self-defence?

9.4 War in Space Has No Good Outcomes

Given the rapidly growing number of satellites, one might be tempted to think that soon there will be too many satellites for any single military to be able to target all of them, and that this might then have a stabilising effect on global security. And to some extent, it might. For why would a state attack another state's satellites if it could not achieve its military aims and would only open itself up to retaliation? Nor could the deliberate creation of Space debris be seen as a quick path to victory (notwithstanding the self-harm it would cause), since the destruction of one or even dozens of satellites would not immediately initiate a collisional cascade.

However, distribution of Space capabilities across thousands of satellites still does not provide perfect security, since all of LEO remains susceptible to a primitive, but catastrophically effective, ASAT weapon. Indeed, should a state determine that its adversaries would be more disadvantaged by the loss of Space-based assets than it would be, it might decide to deny the use of large swathes of LEO to everyone. This could be quickly achieved using a 'pellet ring' – a potential weapon that was identified during the Cold War and that might have seen

further development if the US Strategic Defense Initiative ('Star Wars') had been realised.[37]

A pellet ring involves dispersing a very large number of particles – such as three-millimetre steel balls – into an orbit that ensures many crossings of satellites in a constellation chosen for targeting. A nearly polar orbit dispersal would work well in attacking constellations with low to moderate inclinations, while a low-inclination orbit dispersal would work well against a constellation with polar orbits.

For illustration purposes, let us assume that a pellet weapon disperses 100 million particles with a low change in velocity (Δv). An approximate timescale for disabling a constellation is found by $T \approx \frac{P}{(2N\sigma)}$, where N is the 'column density' of particles released in the attack (i.e. the number of particles per area);[38] σ is the typical satellite cross section, including solar panels; and P is the orbital period at the altitude of the attack. The factor of two arises because each satellite will pass through the ring's column density twice per orbit. To provide some definitive numbers, consider an attack at an altitude of 550 kilometres. Further assume that σ is ten square metres and the dispersal of particles is confined to an altitude range of about ten kilometres. In this case, N is approximately 230 per

[37] The idea of using pellet swarms, Space mines and Space shrapnel as counterspace measures is well known, with pellets and shrapnel being part of Soviet ASAT weapons, although these were not designed to be pellet ring weapons. See Kurt Gottfried and Richard N Lebow, 'Anti-satellite weapons: Weighing the risks', in Franklin A Long, Donald Hafner and Jeffrey Boutwell, eds., *Weapons in Space*, 1st ed. (New York: WW Norton & Company, 1986) 147. A broad overview of ASAT weapons and ballistic missile defence can be found in the following publication of the Soviet Scientists' Committee for the Defense of Peace against the Nuclear Threat: Yevgeni Velikhov, Roald Sagdeev and Andrei Kokoshin, eds., *Weaponry in Space: The Dilemma of Security*, translated by Alexander Repyev (Moscow: Mir Publishers, 1986). Brief but specific references to pellet rings are found in Tom Wilson, 'Threats to United States space capabilities' (2001), Commission to Assess United States National Security Space Management and Organization, online: spp.fas.org/eprint/article05.html; David Evans, '"Star Wars" Will It Work?' *Chicago Tribune* (23 May 1987) online: https://www.chicagotribune.com/news/ct-xpm-1987-05-24-8702080800-story.html.

[38] If 'column density' is an unfamiliar term, think of the following: Suppose you enter a dusty room, with small dust particles uniformly suspended in air throughout the room. The volume density of the dust in this case is just the number of dust particles in the room divided by the room's volume. Now instead, imagine looking at a wall directly across the room and imagine a column extending from the wall to you. All the particles in the column can be counted to give a number of particles per column area (with the area being the base of the column). If you were to walk across the room to the wall, the total number of dust particles you would go through can be estimated by taking the cross section of your body (your area) times the column density. A satellite going through a pellet ring is similar.

square kilometre. The orbital period is about 96 minutes, so the typical time for a collision with any given satellite is about 15 days. This leads to a reasonable expectation that the entire constellation will be effectively destroyed in about one month, while suffering losses of individual satellites almost immediately.

Of course, the ring of particles takes a bit of time to form. A ring ten kilometres wide would require about a month to fully form through 'orbital shear', which occurs because different altitudes orbit at different rates, thus spreading an initial clump of material into a ring. But because this timescale is similar to the timescale for destroying the constellation, and because impacts will begin as soon as some shearing occurs, the time involved in ring formation is not a major limiting factor.

Finally, we should assess whether 100 million is a plausible number of particles. Assuming randomly packed spheres of about three millimetres in diameter, we would need just over two cubic metres of volume. If they are steel balls, then the mass would be around 11 tonnes – about half the payload capacity (to LEO) of a Proton-M rocket. Even then, coarse sand might be easier, weigh a bit less, and work just as well. At any of these particle sizes, collision avoidance manoeuvres are not practical, since the particles are too small to be tracked. The constellation operator might try to change the altitudes of some or all the satellites to avoid the pellet ring, but doing so would be highly disruptive, likely cause accidents, and thus make the attack at least partially successful.

As the target constellation became disabled, dead satellites would undergo collisions with the existing debris field and add to the effectiveness of the attack. Should the attack be at a sufficiently low altitude, such as 550 kilometres, gas drag would then cause the debris to decay, destroying all satellites below that altitude over time. Moreover, nothing prevents multiple pellet rings from being launched at once, to target different altitudes simultaneously.

If dispersing 100 million steel pellets seems like an unfeasible act, it is not. As we explained in Chapter 6, the United States did something similar in Project West Ford, dispersing nearly 500 million copper dipoles in Earth orbit in 1963, intended for enabling long-range communications.

A pellet ring was deemed impractical during the Cold War because mega-constellations did not exist and a constellation of 'battle stations' for Space-based missile defence initiatives was never realised. But recent changes in Earth's orbital environment and in the use of Space assets could make actions that were impractical in the past more than conceivable today, including not only this but other types of counterspace activities.

We began this book with the observation that long-term solutions to grand challenges in Space require approaches that integrate multiple disciplines. We end with a discussion of the pellet ring, not to be disheartening, but to emphasise the essential nature of transdisciplinary, policy-oriented research. Instead of focusing their efforts on international arms control, policy makers have, until very recently, seized upon satellite constellations as providing protection against ASAT weapons – while overlooking their vulnerability to something as simple as dumping a playground's worth of sand into orbit.