Environmental Security Above the Atmosphere: A Primer

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Introduction

As we enter the fourth industrial revolution, life is increasingly reliant on infrastructure which orbits the Earth. From collecting data on climate change, to the early-warning of nuclear attack, satellites now provide an array of benefits. Yet for decades outer space was not seen as an "environment" in need of protection - used instead as a dumping ground for used-up rockets and dead satellites. The result is that out of around 170 million human-made objects in orbit, less than 1500 are functioning satellites (ESA N.D.). Some scientists have warned that this is unsustainable and space may one day become so polluted that satellites will no longer be safe in their orbits. Multiple countries are researching and testing anti-satellite technologies which could exacerbate this problem. A war between major military powers today would likely extend to space, potentially with global consequences. Complicating matters further, outer space experiences what has been termed "space weather," phenomena largely the result of solar activity. Space debris and space weather both have the capacity to disable orbiting satellites. This poses a number of questions for those interested in moving towards a more sustainable future. What kind of threats to the space environment do we face? How resilient are we now, and what steps can be taken to mitigate risks? Who might be affected by changes in the space environment? At the time of writing, in 2017, the many (often unseen) benefits of space technology can no longer be guaranteed to continue into the future. Humanity will require the political will to take steps to mitigate the prospect of negative consequences, or failing that a great deal of luck. If not, the space environment and its associated benefits will be lost for future generations.

This report was envisaged as an easily accessible source of information for those interested in environmental issues, but not yet familiar with the policy issues of outer space. Discussion on the topic is too often cluttered with scientific and military jargon, so steps have been taken to limit this as much as possible in this report. This report was produced as a result of collaboration between the Schumacher Institute and the Economic and Social Research Council's South West Doctoral Training Centre. Additionally, part of this project involved holding an interdisciplinary workshop bringing together participants from a wide range of perspectives and approaches. The participants of our "Day

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Without Space” workshop have my thanks for the insights they shared, particularly on the problems of mitigation and notions of distributive justice which have been incorporated into this report.

The discussion in this report begins with an outline of the state of affairs in orbit today. It then moves on to outline the risks of space debris and space weather. Next, the report briefly envisages scenarios of varying degrees of severity and proceeds to contextualise these risks in terms of resilience and potential mitigation strategies. Finally, the report evaluates who stands to lose from a degraded space environment and concludes that the most pressing concern to be addressed is the prospect of a catastrophic cascade of space debris.

Politics doesn’t respect the Karman Line: the Who, What, Where and Why of Outer Space

If we are going to discuss the space environment, we first need to ask: where does outer space begin? The Karman Line is one answer to this question, it being the height at which it is impossible to stay aloft with the aerodynamic lift from wings (NASA 2005). We can see the Karman Line definition as the product of a blend of the laws of physics and the social/political world of humans. It is a boundary that would-be space-farers must acknowledge, yet politics does not respect the Karman Line. As the strategist Bleddyn Bowen (2015) argues, ‘space warfare is the continuation of terrestrial politics by other means.’ For our purposes here, we can widen this a little to say that *all* human activity in space is the continuation of terrestrial politics (and economics) by other means. After all, what would be the point of doing *anything* in space unless it had some relevance back on the surface? A good starting point, then, is to recognise that human action on Earth can affect matters in orbit, and vice versa. Consequently, this report makes no hard distinction between “space politics” and “terrestrial politics,” or the “Earth environment” and the “space environment.” Instead, when we are talking about outer space, we are really talking about relationships which repeatedly cross the Karman Line, creating complex connections with political, technological and environmental dimensions. With complexity and connectivity comes the possibility of unintended consequences – which we will move on to discuss very shortly. We can use the notion of the “space environment” as a useful shorthand to narrow our inquiry down to those environmental problems which occur above the atmosphere.

We can’t really talk about the risks and opportunities of the space environment without an idea of who is “in” space today. Space today is primarily populated with objects owned[2] by the big

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[2] This is perhaps a clumsy way to gauge influence in space, but it serves as a reasonable approximation here.

three space powers – the United States, China and Russia – plus the European Space Agency (or ESA for short) and India (who are big players but not quite in the same league). The US and Russia famously engaged in a “space race” in the 1950s and 1960s, establishing them as the two-leading space-faring nations until very recently. The United States remains the most prolific satellite-launching state, with nearly 600 in orbit at the time of writing. However, China has overtaken Russia in satellite numbers, with nearly 200 to Russia’s 135 (UCS 2017). In all, there are more than 70 nations with at least one satellite, a figure which tends to increase every year. This is compared to the dozen states and organisations which have the ability to actually launch their own satellites. This disparity can be explained by the sheer difficulty of developing rockets (as the saying goes, it’s rocket science) and the willingness of countries to sell a spot on their launchers to other countries.

Answering “what” is in space goes hand-in-hand with talking about “why” humans have gone to the effort of placing objects in space. Space provides a unique vantage point from which to observe the Earth and communicate over the horizon. Historically, most activity in space has ultimately had some kind of military application. The first satellites were launched atop rockets which were simultaneously developed for delivering nuclear weapons[3]. The “hysteria” of Sputnik was not so much the fear of a “Soviet Moon” innocently beeping at America, but rather the demonstration of the Soviet capability to drop nuclear bombs on American cities[4]. Into the early 1960s, the superpowers were already beginning to use space for spying on each other (both photo- and electronic intelligence), and for both military and civilian communications. Today, large military powers such as the US, China, and Russia all rely (to varying degrees) on satellites to make their armed forces function properly. Satellite networks help guide precision weapons, allow commanders to talk to one another, predict the weather, and help locate enemies. Perhaps the most critical of these are the satellites which “stare” at the surface of the Earth with infrared sensors, looking for the hot exhaust of nuclear missiles as they launch. By detecting missiles at launch, rather than with a radar as they come over the horizon, the US and Russia have been able to add crucial decision-making time to determine if they are really under attack before launching their own nuclear weapons in response. Overall, a little over half of the functioning satellites in orbit today are for some kind of military application (UCS 2017). This means that, for good or ill, when we are discussing the environmental security of space we are also inevitably discussing the military security of the world’s largest military powers.

Space may be a heavily militarised realm, but it is also increasingly tied into how post-industrial societies function. It is usually difficult to see exactly how space technology fits into everyday

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[3] See, for example, the R-7 Semyorka which launched *Sputnik 1* and the Atlas missile which was used both as a nuclear delivery system and to launch the first American into orbit, John Glenn (see FAS 1999 and 2000).

[4] For more on this, see Killian (1977), Osgood (2000) and Neufeld (2013)

activities on the surface – these are services which we just assume will "work." The best example of this is the Global Positioning System, known more commonly as GPS. Originally developed for the sole use of the military, since the year 2000 the American government has provided a civilian GPS signal at no cost to users (GPS.gov 2016). Simply put, the 32 satellites of the constellation (the space geek term for the satellite equivalent of a flock) emit signals which tell the receiver the time very precisely. By receiving from at least three GPS satellites, a receiver can use the tiny differences in the time stamps of the signals to determine its own location. Nearly every smart phone has a GPS receiver, meaning almost all of us in wealthy countries carry a piece of space technology with us on a daily basis. On-demand space-based navigation might seem a trivial luxury, but the American government estimates that efficiency savings on transport benefit the American economy to the tune of $25 billion per year (Leveson 2015: VIII, see also Stenbit 2016). Perhaps more seriously, precision timing is required for many financial transactions, including those undertaken at the world's largest stock markets, a relatively recent development (Jackson 2013, Divis 2014). Similarly, data moving through the internet is given a precise timestamp to ensure packets of information can be reassembled on arrival in the correct order (Williams 2012). In both the cases of financial transactions and data transfer, if the GPS signal was to be lost then there would likely be economic chaos in the short term. It is unknown how long these effects would last, but it is difficult to imagine how a ground-based system could quickly be built to replace the functions of GPS[5]. As Williams (2012) points out, the precise atomic clocks required are too cumbersome to provide every network with one.

Not all space systems are as fundamental to developed economies as GPS. They are still incredibly useful, and similarly difficult to imagine replacements for. Without weather satellites, predictions would have to based entirely from data collected on the ground, which would be less flexible and more costly. Environmental science benefits enormously from the ability to observe the ground and the atmosphere from a high vantage point. Systems like LANDSAT help farmers determine how much irrigation is required for crops, for example (see NASA/USGS 2017 for more). Before the advent of space-based relays, communicating across oceans required expensive under-sea cables. Global communications would be much more costly, and therefore less accessible, without satellites. These are just a handful of benefits and capabilities derived from space technology. Taken as a whole, what we might consider non-essential space capabilities still make life safer, more convenient, and more predictable.

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[5] As Williams (2012) points out, the precise atomic clocks required are too cumbersome to provide every network with one.

Before we turn to the problems of environmental security in space, it is worth quickly outlining some basics about orbital mechanics – the physical laws which govern how objects behave in space. Space is not all that far away. Discussing the Karman Line earlier, we saw that a commonly agreed upon boundary between the atmosphere and outer space is 100km. For comparison, a jet liner flies at about 13km (BA N.D.) and high-flying spy planes like the SR-71 flew at nearly 26km (NASA 2009). The International Space Station orbits 400km up, so when it passes the Schumacher Institute office in Bristol, it is actually closer to us than Brussels (NASA 2011). GPS satellites orbit a lot further up again, around 20,200km (GPS.gov 2017). Finally, the most precious orbit is geosynchronous, or GEO for short. This is a ring around the Earth 36,000km above the equator. Spacecraft which can maintain this orbit appear to "hover" above one point on the surface below because they are travelling as fast as the Earth is spinning. The GEO ring is the only place this can be achieved without using enormous amounts of fuel to maintain a position.

So, if space is not that far away, why is it so difficult to put things in orbit? The answer is that maintaining an orbit is much more about speed than it is height. A spacecraft needs to be high enough to avoid the worst of the drag put up by the atmosphere, but as we have seen that is a mere 100km. Instead, most of a rocket's energy goes into getting lateral velocity. To maintain an orbit in low Earth orbit (LEO), something needs to be travelling at about 7.5km/s (about 40,000km/h) – a speed so fast that as the spacecraft falls back to Earth under the force of gravity, it "misses" the atmosphere and keeps going (ESA 2017, Seifert and Seifert 1964: 46-47). One way to think about an orbit, then, is an object constantly falling at an incredible speed, and with so little to slow it down that it continues to fall for years. To maintain an orbit higher up, more energy needs to be put in which also means more energy is required to slow it down. This is why some of the oldest human-made objects in space are still in orbit more than 50 years later – they have hardly slowed down since they were launched (see www.stuffin.space to explore for yourself).

Risks of Space Debris

'"What goes up must come down" does not necessarily apply to satellites' – (Seifert and Seifert, 1964: 48)

Human activity in space has left its mark. More accurately, it has left around 170 million mementos of the thousands of space missions undertaken since Sputnik (ESA N.D). Discounting the 1500 or so functioning satellites, this is known as space debris or space junk. One of the most frequently republished photos of the Earth from space was taken by Apollo 17 in 1972 (NASA 2017) and has likely helped shape public perceptions of outer space as a pristine, untouched expanse. An easy assumption to make is that space is simply so huge that no matter how much human junk is left in orbit, there will be no problem. In one sense, this is not incorrect – space is unimaginably huge. The problem is that space debris is heavily concentrated in orbits which have proven especially useful to humans – Low Earth Orbit and Geosynchronous Orbit. The volume of space debris is now becoming so large in these areas that accidental collisions are starting to occur between pieces of debris, and in some cases with functioning spacecraft. This casts serious doubt on how sustainable current behaviour in space really is.

The good news is that the risk of injury or property damage from space debris on the surface is vanishingly small[6]. Space debris primarily poses a threat to other satellites, the satellites that so many countries rely on to go about their day-to-day activities. Another piece of good news is that orbital space is, to an extent, self-cleaning. Because there is no definitive point at which the Earth's atmosphere ends, even objects orbiting very high up still occasionally collide with molecules of gas, slowing them down. This is much more pronounced in lower orbits, where without extra velocity added with engines, an object might only stay in orbit for a few years (or even months). If an object gets too slow, it falls back into the atmosphere and usually burns up. At higher orbits, this effect is almost negligible because there is not much atmosphere to speak of. Added to this effect is Earth's "lumpy" gravity and the effects of the Sun, which we will address in turn. The Earth is not a sphere, it is a squashed spheroid. This means that at different times, an object orbiting the Earth has different amounts of mass below it, exerting varying amounts of pull. Added to this, the Moon, Sun and even Jupiter have a measurable effect on the orbital path of objects in space near Earth. Cumulatively, these effects can change an object's orbit to fall into the atmosphere (see for example Lovett 2011a). Lastly, the Sun's rays exert a pressure on objects in space that can change their orbital path too, but this is comparatively a very weak force[7]. The bad news is that this "self-cleaning" effect is not nearly fast enough to keep up with the pace at which human beings are placing objects in orbit, meaning that the amount of debris is growing at an increasingly fast rate.

Existing technology is not capable of detecting objects in orbit which are smaller than 10cm in diameter. This makes it impossible to know the exact total amount of space junk, but we do know that there are more than 29,000 pieces which can be tracked (ESA N.D.). They vary in size from the size of a tea cup to the size of a medium-sized family car. It might sound like a small number, but these pieces of debris are concentrated in very useful orbits. Polar orbits – flight paths which bring satellites close

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[6] Disasters such as the crash of a defunct, nuclear powered Russian satellite, are vanishingly rare (David 2009).

[7] For an unusual use of this effect, see NASA (2013).

to the Earth’s poles – are a cheap way for one satellite to view nearly the whole surface over time. As the satellite travels through space, the Earth spins beneath it. Given the right orbit and enough time, this can be a cost-effective way to map crop yields, or make maps (among other things). All polar orbits have one bit of space in common, however: the bit above the poles. This has created a crowded intersection of orbits. In 2009, this crowding led to an accidental collision between a dead Russian spy satellite and a communications satellite, ploughing into each other at a mind-boggling 10km/s (Weeden 2010a). The result was a huge spray of broken pieces of both satellites which slowly distributed themselves into even more polar orbits. Logic would indicate that the risk of a future collision over the poles is now even higher - more objects competing for the same bit of space - although the mathematics are so complex that it is impossible to know exactly by how much the risk increased (see Lewis 105 for a great explainer).

Another source of accidental debris creation come from the sometimes-explosive malfunctions satellites can experience in orbit. Historically, this was a problem with spent rocket stages – the top part of a launcher which provided the last “push” into an orbit for satellites – which would slowly heat up in orbit. Leftover fuel and gas in the tank would also slowly heat up, eventually causing the tank to explosively burst, creating more pieces of debris (ESA 2013). With more awareness of this problem, space-faring states have taken steps to limit this risk with a good degree of success. Satellites themselves can be at risk of explosive failure. The US military weather satellite system, the Defense Meteorological Support Program, has suffered from suspected catastrophic battery failure on a few occasions, destroying the satellites in those cases and creating new pieces of debris. More recently, a number of satellites have broken up for unknown reasons in geostationary orbit, presumably due to technical failure (or perhaps a collision with debris) (see Berger 2017).

In addition to accidental causes, deliberate actions have also been taken to destroy objects in orbit. There are various ways in which one might disable a satellite. Taken together, these technologies are known as “Anti-satellite weapons,” or ASAT for short. The most notable and destructive of these incidents was in January 2007 when the Chinese military demonstrated a system capable of intercepting satellites, resulting in the destruction of an aging weather satellite. This event added several thousand new pieces of debris, a roughly 25% increase in the total amount of debris (see Weeden 2010b for more). At the time of writing, nearly ten years later, much of that debris remains in orbit and has now been fairly evenly distributed into various low earth orbits (due to the factors of orbital mechanics outlined earlier). Pieces of debris from this event have even caused the International Space Station to manoeuvre to avoid a potential collision (Malik 2012). The US demonstrated a similar capability the following year on one of their own malfunctioning satellites, officially to prevent the tank of highly toxic rocket fuel surviving re-entry and poisoning people on the ground. Russia possesses similar technology which it demonstrated during the Cold War, and it is likely that the Indian government could also develop ant-satellite technology if it chose to.

Collectively these causes may be leading to the "Kessler Syndrome," a self-propagating cascade of collisions named after Professor Donald Kessler[8] (with Cour-Palais 1978) who began to predict the problem in the late 1970s. He predicted that there would eventually be enough debris that pieces would collide with each other, breaking into smaller pieces which were then more likely to collide other pieces, repeating the process. Unchecked, this process would eventually leave nothing but tiny particles in a huge debris field. It would be impossible to orbit satellites in areas that had experienced the culmination of Kessler Syndrome. If Professor Kessler is correct, this kind of process could result in humanity losing access to orbital space for hundreds, if not thousands of years. All of the benefits of space – military, economic and scientific – would be lost, and very difficult to fully replace.

Risks of Space Weather

The Earth is surrounded by naturally occurring radiation of various kinds. Radiation is a major factor in determining how long a satellite will operate – eventually components become irradiated, degrade in function and eventually stop working entirely (see Howard and Hardage 1999: 10 for a scientific overview). The most powerful source of space weather is our Sun, pumping out not just visual light, but radiation across the electromagnetic spectrum. The Sun's rays interact with the Earth's magnetic field and the Van Allen belts, two donut shaped rings which encompass the Earth that are made up of charged particles trapped in orbit around the Earth by its magnetic field. As the output of the Sun varies, conditions around the Earth, and especially in the Van Allen belts, vary too. This is why it is useful to think of these effects as a kind of weather – a complex system with variable impact on human life. Efforts to understand and manipulate space weather in the past included detonating nuclear weapons at high altitudes. As one might expect, this was environmentally disastrous. The most infamous 1962 test, Starfish Prime, destroyed some of the satellites in orbit at the time as the radiation from the weapon left charged particles trapped in orbit around the Earth (Hollingham 2015). At the time, space was not relied upon for essential services, so there was little disruption to activity on the surface. Luckily, the risks of using nuclear weapons in space seems to have become well understood, and has not occurred for many decades. Space weather is an even more unpredictable risk to space

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[8] Whether this is inevitable or not is still being debated in the scientific community. See Lewis (2015) for more.

technology than debris. The good news is that scientists are sceptical whether a truly catastrophic event will occur. There has been no recorded solar activity, even at "solar maximum," which would disable every satellite in orbit simultaneously (NASA N.D.). Having said this, a so-called "Carrington event" (named after a Victorian scientist who observed a massive solar flare in 1859) would certainly temporarily cause enormous disruption to space services (Lovett 2011b).

Imagining scenarios: likely, unlikely and nightmares

To give a sense of the huge variation in the scale of consequences and levels of risk, the report now quickly outlines three imagined future scenarios. It is impossible to know the exact probabilities involved, so these situations can only hope to give a flavour of the risks we face in the space environment.

A likely scenario is that space debris strikes a key satellite in low earth orbit in the next few years, much as in 2009. In the short-run disruption would be minimal, depending of course on which satellite was destroyed. No government response would be required initially, and people in the ground would be unlikely to detect any loss in space-derived services. In the long-run, however, the debris resulting from the collision would increase the risk of future collisions. Depending on how much debris was caused, more serious debris mitigation policies might have to be enacted.

An unlikely event would be a solar flare which disables unprotected satellites over one hemisphere of the Earth – a "Carrington event" outlined above. Key military satellites are likely well-protected against this kind of radiation (due to its similarities to the effects of nuclear weapons) so essential systems like GPS would hopefully be unaffected. The damage would be concentrated on civilian communications, environmental and agricultural satellites. To replace them would take years and billions of dollars. In this scenario, however, the largest amount of damage would be to power grids on the surface, causing much more disruption than the effects to space systems. Perhaps the most dangerous effect of all would be the likely panic that affected populations would experience under such unusual circumstances.

A highly unlikely and but highly consequential scenario would be a full-scale war in space with far-reaching effects both in orbit and on the surface. The most commonly discussed scenario would be some kind of US-China conflict in the South and/or East China Seas. According to some American observers, China would likely launch anti-satellite attacks early on in such a conflict in order to damage the technological advantage the American military has over the Chinese military. For this to have any meaningful strategic effect, China would have to launch a large number of ASAT missiles (Sankaran 2014). If these were of the “kinetic” type used in 2007, a Kessler event would be much more likely, or if the attacks were particularly intense, a cascade could be triggered at that point. An additional risk comes from the intersection of an international conflict and the potential loss of nuclear early-warning and command systems. In the very worst-case scenario, the US would be left with no way to detect a pre-emptive nuclear strike by China, and with poor prospects of communicating with its nuclear forces as the crisis unfolded. The result could well be an accidental nuclear war with global ramifications – consequences far in excess (and more concerning) than the effects on the space environment (for a fruitful discussion on this topic see BotAS 2015).

Mitigation and resilience

The questions of how resilient we are, or how we might mitigate the risks outlined so far, depend heavily on what risks we are talking about. As we have seen from the three brief imaginary scenarios, attempts to prevent or respond to the consequences of degradation of the space environment would need to vary to fit the specific consequences in question. There is a huge range of possible levels of risks and consequences, so this report cannot be exhaustive. Instead, it aims to raise some of the key issues on matters of mitigation and resilience.

Despite the grim outlook in the long-run, it should be noted that there is a reasonable degree of resilience to the risks outlined in this report. Space weather may be unpredictable, but current models do not predict totally catastrophic results from solar activity. In a sense, this risk may not be worth mitigating against since it is quite unlikely (and key systems are already resilient to these effects). Similarly, even the economies most heavily dependent on space services are probably capable of absorbing the loss of some space services. The loss of a single satellite to a debris strike might damage some communication links, or limit our ability to collect data on climate change. Yet this outcome would be unlikely to cause widespread panic and, assuming no Kessler event was triggered, could be replaced with new satellites. The key space system for many advanced economies, GPS, is already very resilient, both to debris and to solar radiation. It has on-orbit back-up satellites and orbits in a relatively uncrowded area of space. Unless there was a major war in space in which many kinetic ASAT weapons were used, GPS would likely remain functioning. If this nightmare scenario were to occur, then as one attendee of the Schumacher Institute’s workshop observed, we would have much bigger problems to worry about. One concern is that the US might shutdown the GPS signal during a crisis, but eventually more global navigation systems will be functioning, such as the European Galileo system and Russia’s GLONASS.

The risk which must be addressed is the rapid increase in orbital debris because a Kessler event would have such highly persistent negative after-effects. The current guideline that objects should be planned to de-orbit within 25 years is optional, and frequently ignored (Selding 2015). Given the global nature of the problem of space debris, the ideal level at which to address these concerns would seem to be at a multilateral, international level of governance. The closest we got to such an international agreement of this kind was the European Union’s ‘International Code of Conduct for Outer Space Activities,’ which was proposed at the UN but, at the time of writing, has led to no formal adoption. Despite its limited success so far, the Code of Conduct, or something like it, is probably the best starting point for creating a regime which could begin to address the problem of space debris (see the Secure World Foundation (Johnson 2014) for more detail on this). Participants at the Schumacher “A Day Without Space” workshop came to the consensus that it could still be a success even if some powerful states did not sign-up. This is because it would serve as a good foundation for more binding and enforceable regulations later on. The example of the international law governing the high seas was raised as one example of a successful regulatory regime which already exists and could be used as a model in the future. Coupled with stronger regulation, it is also very likely that “active” mitigation will be required – simply put, physically removing some of the worst offending pieces of debris. High mass, dead satellites (such as the 11-ton ENVISAT) would be well-worth removing. Technology is already being developed to achieve this, but debris removal will be sufficiently expensive that it will also require a great deal of political will too. Under current international law, objects in orbit are ultimately under the jurisdiction of the state that launched them (UN 2002: 13). As a result, without the express permission of the owner of a piece of debris it cannot be removed. On a more positive note, the Outer Space Treaty of 1967 also recognises that owners of objects in space are liable for the damage they cause (UN 2002: 13-14). This may be one impetus for states to clean up mess they have left in orbit. More responsible behaviour in space will almost inevitably raise the cost of access to space, meaning that non-compliance in a future debris mitigation agreement would give uncooperative states an economic advantage. This can already be seen to an extent in the price differential between ESA launch costs, who observe their own “Clean Space” requirements, compared with other launchers who impose no such restrictions on themselves. The governments who take the lead on space debris mitigation will have to swallow the costs in the short-run, as they attempt to convince other space-faring states to join the regulatory regime. This would inevitably be a large stumbling-block, but one that must be overcome if outer space is to be preserved.

Evaluation: Who stands to lose?

As we have seen, the space environment has some of the hallmarks of a global commons with the capacity to be beneficial to enormous swathes of the population. As it stands, however, the biggest beneficiaries of the space environment are the big space powers and the industrialised countries which rely on the services that satellites provide. This means that in the short run, catastrophic events in space would mostly (directly) damage Western economies. The long-run negative consequences would be globally distributed, however. On this basis, losing access to space for hundreds of years because the major powers refused to act would be a gross injustice committed against countries that are weaker and poorer today. If the benefits of space-based communication, navigation, timing, and science are to be shared more equally at some point in the future, then logically steps must be taken to preserve access to the medium which makes these benefits possible. Taking an optimistic view, because the big space powers have so much to lose if the space environment is compromised there seems to be some hope that they will take these steps before the problem becomes too acute. International cooperation is never straightforward, however, so campaigners for the protection of the space environment must continue to pressure their governments to continue to pursue a global, regulatory solution. Preserving the space environment must be a component of broader efforts to govern for global equity and make society more sustainable.

Suggested further reading and news sources:

Moltz, J. (2008) *The Politics of Space Security: Strategic Restraint and the Pursuit of National Interests*, Stanford University Press: Stanford – An excellent overview of how military and environmental space security overlap.

SpaceNews – A standard industry news source, accessible without a pay wall. See: http://spacenews.com/

The Secure World Foundation – Regular updates on space sustainability and a source of technical expertise. See: https://swfound.org/

Union of Concerned Scientists – Expertise on physics and a focus on the intersection of nuclear weapons and outer space. See: http://www.ucsusa.org/nuclear-weapons/space-security#.WYr34VWGOUk

Bibliography:

Berger, E. (2017) ‘A satellite may be falling apart in geostationary orbit [Updated],’ *Ars Technica*, Available at: https://arstechnica.com/science/2017/07/a-large-satellite-appears-to-be-falling-apart-in-geostationary-orbit/ Accessed: 08/08/2017

Bowen, B. (2015) *Spacepower and Space Warfare: The Continuation of Terran Politics by Other Means*, Available at: http://cadair.aber.ac.uk/dspace/handle/2160/43434 Accessed: 08/08/2017

British Airways (N.D.) ‘Boeing 777-300,’ Available at: https://www.britishairways.com/en-gb/information/about-ba/fleet-facts/boeing-777-300 Accessed: 08/08/2017

Bulletin of the Atomic Scientists (2015) ‘Space weapons and the risk of nuclear exchanges,’ Available at: http://thebulletin.org/space-weapons-and-risk-nuclear-exchanges8346

David, L. (2009) ‘Old Nuclear-Powered Soviet Satellite Acts Up,’ Available at: https://www.space.com/6322-nuclear-powered-soviet-satellite-acts.html Accessed: 08/08/2017

Divis, D. (2014) ‘Financial Networks Shifting to GPS-Stamped Precise Time,’ *InsideGNSS*, Available at: http://www.insidegnss.com/node/4355 Accessed: 08/08/2017

European Space Agency (N.D.) ‘How many space debris objects are currently in orbit?’ http://m.esa.int/Our_Activities/Space_Engineering_Technology/Clean_Space/How_many_space_debris_objects_are_currently_in_orbit

European Space Agency (2013) ‘Rocket Body Explosions,’ Available at: http://m.esa.int/spaceinimages/Images/2013/04/Rocket_body_explosions Accessed: 08/08/2017

European Space Agency (2017) ‘EUROPEAN CONFERENCE ON SPACE DEBRIS RISKS AND MITIGATION,’ Available at: http://www.esa.int/Our_Activities/Operations/Space_Debris/European_conference_on_space_debris_risks_and_mitigation/(print) Accessed: 08/08/2017

Federation of American Scientists (1999) ‘SM-65 Atlas,’ Available at: https://fas.org/nuke/guide/usa/icbm/sm-65.htm Accessed: 08/08/2017

Federation of American Scientists (2000) ‘R-7 – SS-6 Sapwood,’ Available at: https://fas.org/nuke/guide/russia/icbm/r-7.htm Accessed: 08/08/2017

GPS.gov (2016) ‘Selective Availability,’ Available at: http://www.gps.gov/systems/gps/modernization/sa/ Accessed: 08/08/2017

GPS.gov (2017) ‘Space segment,’ Available at: http://www.gps.gov/systems/gps/space/ Accessed: 08/08/2017

Hollingham, R. (2015) ‘The Cold War nuke that fried satellites,’ *BBC News*, Available at: http://www.bbc.com/future/story/20150910-the-nuke-that-fried-satellites-with-terrifying-results Accessed: 08/08/2017

Howard, J. and Hardage, D. (1999) ‘Spacecraft Environments Interactions: Space Radiation and Its Effects on Electronic Systems,’ Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19990116210.pdf Accessed: 08/08/2017

Jackson, W. (2013) ‘The serious side of GPS, where timing is everything,’ *GCN*, Available at: https://gcn.com/articles/2013/11/12/gps-timing-position.aspx Accessed: 08/08/2017

Johnson, C. (2014) 'Draft International Code of Conduct for Outer Space Activities Fact Sheet,' Available at: https://swfound.org/media/166384/swf_draft_international_code_of_conduct_for_outer_space_activities_fact_sheet_february_2014.pdf Accessed: 08/08/2017

Kessler, D. and Cour-Palais, B. (1978) 'Collision frequency of artificial satellites: The creation of a debris belt,' *Journal of Geophysical Research Space Physics*, Vol. 83, No. A6, pp. 2637-2646

Killian, J. (1977) 'Sputnik Fever,' *The Sciences*, Vol. 17, No. 6, pp. 6-9

Leveson, I. (2015) 'GPS Civilian Economic Value to the U.S. Interim Report,' Available at: http://www.performance.noaa.gov/wp-content/uploads/2015-08-31-Phase-1-Report-on-GPS-Economic-Value.pdf Accessed: 08/08/2017

Lewis, H. (2015) 'Space debris, Kessler Syndrome, and the unreasonable expectation of certainty,' Available at: https://room.eu.com/article/Space_debris_Kessler_Syndrome_and_the_unreasonable_expectation_of_certainty Accessed: 08/08/2017

Lovett, R. (2011a) 'New Gravity Map Reveals Lumpy Earth,' Available at: http://news.nationalgeographic.com/news/2011/04/110406-new-map-earth-gravity-geoid-goce-esa-nasa-science/ Accessed: 08/08/2017

Lovett, R. (2011b) 'What If the Biggest Solar Storm on Record Happened Today?' Available at: http://news.nationalgeographic.com/news/2011/03/110302-solar-flares-sun-storms-earth-danger-carrington-event-science/ Accessed: 08/08/2017

Malik, T. (2012) 'Space Station Dodges Debris From Destroyed Chinese Satellite,' Available at: https://www.space.com/14398-space-station-dodges-chinese-space-junk.html Accessed: 08/08/2017

NASA (N.D.) 'Space Weather,' Available at: https://hesperia.gsfc.nasa.gov/sftheory/spaceweather.htm Accessed: 08/08/2017

NASA (2005) 'A word about the definition of space,' Available at: https://www.nasa.gov/centers/dryden/news/X-Press/stories/2005/102105_Schneider.html Accessed: 08/08/2017

NASA (2009) 'Past Projects: SR-71 Blackbird,' Available at: https://www.nasa.gov/centers/dryden/history/pastprojects/SR71/index.html Accessed: 08/08/2017

NASA (2011) 'Higher Altitude Improves Station's Fuel Economy,' https://www.nasa.gov/mission_pages/station/expeditions/expedition26/iss_altitude.html Accessed: 08/08/2017

NASA (2013) 'A Sunny Outlook for NASA Kepler's Second Light,' Available at: https://www.nasa.gov/kepler/a-sunny-outlook-for-nasa-keplers-second-light Accessed: 08/08/2017

NASA (2017) 'Blue Marble – Image of the Earth from Apollo 17,' Available at: https://www.nasa.gov/content/blue-marble-image-of-the-earth-from-apollo-17 Accessed: 08/08/2017

NASA/USGS (2017) 'Landsat Science: Agriculture Archive,' Available at: https://landsat.gsfc.nasa.gov/category/news/agriculture/ Accessed: 08/08/2017

Neufeld, M. (2013) ‘*Eisenhower’s Sputnik Moment: The Race for Space and International Prestige* by Yanek Mieczkowski (review),’ *Technology and Culture*, Vol. 54, No. 4, pp. 998-999

Osgood, K. (2000) ‘Before Sputnik: National Security and the Formation of U.S. Outer Space Policy,’ in Launius, R., Logsdon, J. and Smith, R. (eds.) *Reconsidering Sputnik: Forty Years Since the Soviet Satellite*, Routledge: London, pp. 197-230

Sankaran, J. (2014) ‘Limits of the Chinese Antisatellite Threat to the United States,’ *Strategic Studies Quarterly*, Vol. 4, pp. 19-46, Available at: http://www.cissm.umd.edu/sites/default/files/Limits%20of%20the%20Chinese%20Antisatellite%20Threat%20to%20the%20United%20States.pdf Accessed: 08/08/2017

Seifert, H. and Seifert, M. (1964) *Orbital Space Flight: the Physics of Satellite Motion*, Holt, Rinehart and Winston Inc.: New York

Selding, P. (2015) ‘1 in 5 Cubesats Violates International Orbit Disposal Guidelines,’ *SpaceNews*, Available at: http://spacenews.com/1-in-5-cubesats-violate-international-orbit-disposal-guidelines/ Accessed: 08/08/2017

Stenbit, J. (2016) ‘Spectrum Repurposing and Interference with Space-Based Positioning, Navigation, and Timing (PNT) Services,’ Available at: http://www.gps.gov/governance/advisory/recommendations/2016-06-letter-to-excom.pdf

Union of Concerned Scientists (2017) ‘UCS Satellite Database,’ Available at: http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.WYnPfFWGOUk Accessed: 08/08/2017

United Nations (2002) *UNITED NATIONS TREATIES AND PRINCIPLES ON OUTER SPACE: Text of treaties and principles governing the activities of States in the exploration and use of outer space, adopted by the United Nations General Assembly*, Available at: http://www.unoosa.org/pdf/publications/STSPACE11E.pdf

Weeden, B. (2010a) ‘2009 Iridium-Cosmos Collision Fact Sheet,’ Available at: https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf Accessed: 08/08/2017

Weeden, B. (2010b) ‘2007 Chinese Anti-Satellite Test Fact Sheet,’ Available at: https://swfound.org/media/9550/chinese_asat_fact_sheet_updated_2012.pdf Accessed: 08/08/2017

Williams, R. (2012) ‘What is NTP Time and How Does it Benefit Me?’ Available at: http://www.galsys.co.uk/news/what-is-ntp-time-and-how-does-it-benefit-me/#more-1129 Accessed: 08/08/2017