

Somebody's watching over you

You may not see them, but they are there. Orbiting the equator and orbiting the poles, enabling us to communicate on social media and Zoom in the social-distancing age of COVID-19.

They provide our TV news, allow us to phone a friend, check on our relatives and warn us about hurricanes, monitor Antarctic ice sheets, ozone holes, fires and volcanoes. They take care of us and our environment.

But they weren't always there. Before Oct. 4, 1957, our Moon and rocks and space dust from 4.6 billion years ago were all that orbited our planet. And then came Sputnik, the Soviet Union's tiny, basketball-sized beeping satellite.

The U.S. followed, with the launch of Explorer-1 on Feb. 1, 1958.

These two satellites were followed by weather, communications, commercial and spy satellites, the shells of manned spacecraft rocket engines, and some very weird stuff.

During the last six decades space has become crowded, and some of our orbiting caretakers are in danger.

By the end of 2019, there were more than 2,200 active satellites in orbit, with more than 1,400 in low Earth orbit (LEO).

LEO, low Earth orbit, is an orbit with an altitude between 160 km to 2,000 km (99 mi to 1200 mi) where objects make at least 11.25 orbits around Earth each day. Most human-made objects in outer space are in LEO.

NASA/Goddard Technical Deputy for Space Science Mission Operations, Russell Carpenter, said "if we start to clog up LEO, we can't put up science missions. We want to be able to continue to study the environment. [We will] have to put satellites in higher orbit, which can make doing science more difficult."

John Crassidis, Mechanical and Aerospace Engineering Professor, University at Buffalo, explained that increasing the number of satellites significantly raises the probability of collisions. "[i]f the probability [of a collision] is greater than 1-in-10,000 then people start to get worried," he said.

And it's about to get even more crowded.

University of Texas Associate Professor of Engineering Moribah Jah said LEO "is a finite resource. Most of what we put there never comes back. We risk saturating these orbital highways. We just wouldn't be able to put satellites into those orbits."

Find out how NASA protects astronauts and the International Space Station from space debris impacts. Check out NASA's A Research Guide to International Space Station: Environmental Effects, https://www.nasa.gov/sites/default/files/files/NP-2015-03-015-JSC_Space_Environment-ISS-Mini-Book-2015-508.pdf and Space Debris and Human Spacecraft, https://www.nasa.gov/mission_pages/station/news/orbital_debris.html

The International Space Station orbits in LEO. So does NASA's Earth Observing System fleet, which gathers data on Earth's environment, including its surface, biosphere, atmosphere and oceans.

Carpenter explained the importance of protecting LEO. In order to continue studying the environment satellites would need to be put into higher orbits to avoid collisions, making science more difficult and expensive.

In 2018, the European Space Agency moved its CryoSat 2 satellite from its usual orbit to avoid a potential space junk collision, just a week after issuing a report that there was about 3,600 kg (about 8,000 lbs) of space junk in LEO.

An impact with even a small piece of debris, orbiting at nearly 7.5 km/s (about 17,000 mph) could have destroyed this important satellite.

The \$162 million CryoSat 2 studies ice and glaciers, enabling earth scientists to create 3-D models of the Antarctic ice sheet, melting patterns and sea level changes.

SpaceX, the brainchild of Elon Musk, has already launched 420 Starlink satellites that appear as bright pearls in the night sky.

SpaceX plans to launch 12,000 more satellites within the next seven years, creating a global high-speed broadband internet network accessible from any location on Earth.

SpaceX Starlink satellites have collision detection software, but in 2019, one of its satellites nearly collided with a European Space Agency (ESA) satellite. ESA was forced to move its satellite to avoid the collision.

SpaceX later reported that its failure to cooperate with ESA was due to a communications issue that the company intends to fix.

OneWeb, another global communications company with communications plans similar to those of SpaceX, filed for Chapter 11 in March 2020. The company already launched 74 satellites. It was in the process of securing additional funding when the COVID-19 epidemic created financial problems that stopped additional launches.

It's possible that those 74 satellites will become space junk if OneWeb abandons them.



The International Space Station in LEO. NASA. July 7, 2010.

<https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-orbit-58.html>
public domain

To learn more about Starlink visit:

<https://metro.co.uk/2020/04/24/starlink-satellites-work-12604227/?ito=cbshare>

Twitter:

<https://twitter.com/MetroUK>

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<https://www.facebook.com/MetroUK/>

What is space junk?

Some of the strangest stuff in Earth orbit includes a tool bag lost by an astronaut Heidi Piper, a spatula from the space shuttle Discovery, one of astronaut Ed White's gloves from his June 3, 1965 Gemini 4 spacewalk. During a 2017 spacewalk, astronaut Peggy Whitson lost a thermal blanket that provides protection on the International Space Station.

Space junk is "[a]nything that's not useful anymore. Anything flown off a satellite," Crassidis said. This includes more than 1,100 inactive satellites.

Jah described a U.S. Air Force project that deployed millions of copper needles into LEO. These needles were supposed to provide radio communication capabilities if a nuclear test destroyed the ionosphere, the layer of Earth's atmosphere that reflects radio waves.

Some of the needles are still in orbit.

But not everything stays up there.

In 1992, the Space Shuttle Columbia carried some of Star Trek creator Gene Roddenberry's cremated remains into space in a small capsule, returning it to Earth, rather than increasing the amount of space junk already in orbit.

How much is out there?

To be cataloged, space researchers are required to identify an object's launch location, which can prove extremely difficult, since a lot of space debris has been in orbit for more than 50 years. They also use radar and large telescopes to find space debris.

Lee Jasper, Chief System Engineer at Space Dynamics Laboratory, Kirtland AFB, said that the U.S. Air Force Space Surveillance Network has been cataloging space debris since 1967.

According to Carpenter, they can only track objects larger than a baseball. But smaller items include paint flecks, nuts and bolts.

There is "also a lot of guestimation involved in space debris identification," Crassidis said. Sometimes identification is impossible.

Whose satellite is this?

The United Nations Office of Outer Space Affairs (UNOOSA) maintains a list of all objects launched in space, but sometimes satellites fall through international cracks.

The 1974 Convention on Registration of Objects Launched into Outer Space requires that the launching nation report its activities to UNOOSA. About 90% of the objects in Earth's orbit are

In 2018, a California walnut farmer called the police when he found a strange metal object in his field. A bit of detective work and a call to Vandenberg Air Force Base, helped identify the object as a spent fuel tank of the Iridium 70 communications satellite, which fell out of orbit three days before it was found.

registered, but at least 700 are not.

The NNS-6 and NNS-7 satellites were built by Lockheed Martin Commercial Space Systems for the Dutch International NV Corporation, launched by the French Arianespace SA in France. Once in orbit the satellites became the property of the Dutch company. None of the three nations involved took responsibility for registration.

This may seem trivial, but if one of these satellites crashes, under the 1972 Convention on International Liability Caused by Space Objects, one of these countries would be responsible for paying to remove the junk. But which one?

Who left that trash there?

There is no international space traffic control system.

Active satellites can usually be controlled, but inactive satellites and debris cannot.

Some of these objects move at nearly 36,000 km/hr (22,300 mph), and when they collide, they make a celestial mess. Others simply explode.

Carpenter said “The part that is the most interesting is that these are very rare events, like this pandemic. How much effort do we put into dealing with rare events? How do we make decisions under uncertainty? [This is a] great domain for statisticians.”

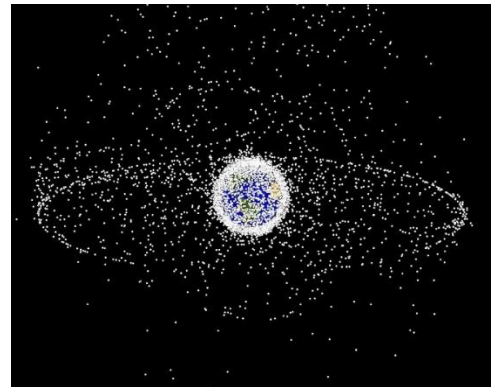
Aaron Rosengren, Assistant Professor in the College of Engineering, University of Arizona, said there are “five explosions per year of things that blow up.”

These explosions, usually the result of non-collisional mishaps, create even more pieces of junk moving at incredible speeds.

Rosengren said that the number of explosions could be reduced by sending commands to satellites before they are inactivated to instruct them to dump their fuel and disconnect their batteries.

The U.S., Japan, Europe and India are big producers of space junk, but Crassidis said that the worst offenders are Russia and China.

In 2007, the Chinese destroyed their own FY-1C satellite during a test, producing about 3,000 additional objects large enough to be individually tracked.



Computer-generated image representing space debris as seen from high Earth orbit. The two main debris fields are the ring of objects in geosynchronous Earth orbit (GEO) and the cloud of objects in low Earth orbit (LEO). NASA Orbital Debris Program Office, February 1, 2005, public domain

https://en.wikipedia.org/wiki/Space_debris

On Feb. 10, 2009, in the first accidental space collision, Russia's nonoperational Cosmos 2251 satellite crashed into an active, polar-orbiting Iridium 33 satellite. This impact created more than 500 pieces of debris.

Aerospace Corporation's Marlon Sorge, Principal Engineer, Space Innovation Directorate, explained that had this been a weather satellite, its destruction would have had an impact on weather forecasting ability.

Space agencies, mission planners and astrodynasticists use models that usually predict collisions and near misses.

But as Carpenter said, this collision "sent a huge message that the models aren't good enough."

Jah and his colleagues at the Advanced Sciences and Technology Research in Astronautics (ASTRIA) program developed software to create "awareness of the trackable population and consistency and inconsistency in opinions of where stuff is."

The team is trying to assess compliance and non-compliance with space laws, policies, and guidelines. "[You] can't enforce what you don't know," Jah said.

"Who is going to get the insurance or pay for it if the insurance rates skyrocket?" Crassidis asked. The answer to his rhetorical question impacts all of us.

Sorge said that additional costs will likely be passed on to satellite service users, meaning nearly everyone on planet Earth.

But increased costs are not the only issue. Collisions will significantly curtail our ability to watch our planet from space.

Jasper explained that "We will have to shield our spacecraft. That increases cost and reduces capability, trading mass for functionality." This means that funding will pay for satellite self-protection, rather than satellite Earth science.

The 25-year plan

Sorge said that international cooperation is required to control space junk.

The Inter-Agency Space Debris Coordination (IADC) Committee, which includes NASA and 12 other space agencies, has adopted a rule that requires satellite operators to move their satellites out of LEO within 25 years of the end of a satellite's life. The satellite would need to be brought back to Earth or kicked into a higher orbit.

Sorge is a member of the NASA delegation of the IADC. He explained that countries have their own space debris simulation models, which yield different results, so committee members meet to understand why their model results differ and to better understand how to remove space junk.

Taking out the trash

Each year, about 300 tracked objects enter Earth's atmosphere on their own. About 100 reach Earth's surface. Most other objects take hundreds or thousands of years to deorbit, far too long given the number of satellites now being launched into LEO.

The Kessler syndrome is a theoretical scenario proposed by NASA scientist Donald J. Kessler in 1978. The density of objects in LEO could become so great that collisions among objects could create a cascading effect. Collision debris could create a chain of collisions, like falling dominoes, destroying satellites on which we all depend.

Carpenter said that a Kessler syndrome would affect human activity by potentially destroying environmental monitoring satellites observing the oceans, soil, and clouds.

In 2017, Jah testified before the United States Senate Committee on Commerce, Science, and Transportation Subcommittee on Space, Science, and Competitiveness. He said that the Resident Space Objects (RSO) catalog operated by U.S. Strategic Command (USSTRATCOM) was inadequate.

Jah said that the RSO has over 24,000 records. More than 18,400 of the catalog objects have been sufficiently tracked, about 1,300 are operational satellites, and the rest are space junk.

Jah tried to impress on the Senate that some of those launching satellites into LEO were behaving based on their own self-interests, rather than considering their impacts on the whole environment. He suggested that the Department of Commerce provide space traffic services, but he was unsure if the Senate had taken any action.

The best laid plans

To be successful, any debris removal method will need to eliminate large pieces of space debris which are likely to do the most damage to other satellites and human space activities. Magnets, harpoons, nets, cubesats and tethers have been proposed for capturing space debris to return it safely to Earth.

"We are looking at a revolution in space, and with that comes a certain set of responsibilities," Sorge said. One of those is removing inactive satellites as well as any debris they leave in LEO.

"If we only remove five large bodies every year, then we can actually significantly reduce the number of collisions in the long run," Jasper said.

But Carpenter said there is currently no practical way to remove space debris.

Active debris removal is "really fun, but super hard," Jasper said, and it requires physical contact with the space junk, changing its motion.

Jasper explained that an object that moves another country's active satellite, even to protect it from a collision, could be viewed as a defensive weapon.

On April 15, Russia launched an anti-satellite missile to test technology designed to remove satellites in LEO. The U.S. Space Force considers it a threat to American satellites.

Universities, private companies and international consortiums are designing and testing creative and clever solutions to removing space debris.

Rensselaer Polytechnic Institute is designing a tiny cubesat called OSCaR that uses a tether system. Each OSCaR should be able to remove four pieces of space junk.

In 2018 a European and South African consortium deployed the RemoveDebris satellite which successfully captured a little cubesat.

Crassidis said that the capture method used by the RemoveDebris satellite uses complicated dynamics, and trying to capture a satellite can destabilize it, making its motion more unpredictable.

Some astrodynamacists and satellite engineers think there are better ways to deal with the space junk that doesn't require actual contact.

In 2016, Rosengren and his colleagues calculated that the gravitational pull of the Moon and sun could be used to move satellites. The team determined that changing a satellite's launch time by as little as 15 minutes could significantly affect whether that satellite could be safely deorbited at the end of its life.

Another possible solution is the Ion Beam Shepherd, proposed by ESA in 2011. The idea behind this technology is simple. Accelerated plasma aimed at a satellite would be used to push it into a safe orbit, without needing to dock with it. This would eliminate inducing even more motion in a difficult-to-capture object.

Developed by a Swiss startup company, ESA's ClearSpace-1 is scheduled for launch in 2025. That spacecraft will capture the Vega Secondary Payload Adapter (VESPA) upper stage that was left in LEO orbit after the 2013 second flight of ESA's Vega spacecraft.

VESPA is similar in size to a small satellite. This mission will provide ESA an opportunity to test this new technology, and, if successful, ClearSpace-1 might be utilized to remove larger



A cubesat is a tiny satellite made of 10 cm x 10 cm x 10 cm units, with a mass of no more than 1.33 kg (about 3 lbs) per unit. These little satellites often use low-cost off-the-shelf components and are primarily used for scientific research. Source: Wikipedia https://en.wikipedia.org/wiki/Cubesat#/media/File:Cubesatkit_1u-skeleton.jpg, CC BY-SA 3.0

space debris.

Space policy

Many of the technological aspects of space traffic management (STM) have been identified and solved. Nations under the auspices of the IADC cooperate and share space debris data.

In the U.S., however, there is a tangled web of governmental agencies involved in satellite licensing and deployment. NASA and the Department of Defense (DoD) have differing space goals, which creates disputes. Resolution has been left in the hands of the Vice President and the National Space Council.

To learn more about space objects, visit:
Stuff in Space
<http://stuffin.space/> Space Track,
<https://www.space-track.org/auth/login>
Celestrak, <https://celestrak.com/>
LeoLabs,
<https://www.leolabs.space/>

The U.S. Department of Transportation licenses commercial launches via the Federal Aviation Administration (FAA), the Federal Communications Commission (FCC) is responsible for licensing commercial satellite communications operators.

The U.S. Commerce Department licenses commercial remote sensing satellites via the National Oceanic and Atmospheric Administration (NOAA). The Office of the Director of National Intelligence and the State Department are also involved.

The Space Safety Coalition (SSC) was formed in September 2019. The SSC consists of nearly 40 space operators, manufacturers, launch providers and insurers. Rather than waiting for governmental agencies to sort out their disputes, the SSC issued its own set of space best practices, incorporating IADC policies, but endorsing a 5-year satellite disposition rule, rather than the 25-year rule.

In 2018, the current administration designated the Department of Commerce as the agency responsible for future STM rules, and for providing space operators with space situational awareness (SSA) data.

On April 6, the White House issued an Executive Order on Encouraging International Support for the Recovery and Use of Space Resources. This directive stated that “Americans should have the right to engage in commercial exploration, recovery, and use of resources in outer space, consistent with applicable law.”

The directive continues: “Outer space is a legally and physically unique domain of human activity, and the United States does not view it as a global commons. Accordingly, it shall be the policy of the United States to encourage international support for the public and private recovery and use of resources in outer space, consistent with applicable law.”

But space is a global commons now, more than ever before, and no pronouncement by any government will change that.

So look up. And when you see a tiny, bright pearl-like dot moving steadily across the sky, remember that it's a satellite, watching over you.

Internet and Other Research Sources

Aerospace Corporation. (n. d.). CORDS: The Center for Orbital Debris Studies.
<https://aerospace.org/cords>

Aerospace Corporation. (2018, May 4). Danger: Orbital debris.
<https://aerospace.org/article/danger-orbital-debris>

AFP. (2017, March 31). Astronaut loses space blanket during historic spacewalk. Seeker.
<https://www.seeker.com/space/astronaut-loses-space-blanket-during-historic-spacewalk>

Allain, R. (2015, September 15). What's so special about low Earth orbit? Wired.
<https://www.wired.com/2015/09/whats-special-low-earth-orbit/>

Bartels, M. (2018, July 10). Europe's ice-watching satellite dodges space junk in orbit.
Space.com. <https://www.space.com/41126-european-satellite-dodges-junk-in-orbit.html>

Bartels, M. (2018, December 5). Tiny satellites pose a swarm of opportunities – and threats.
Space.com. <https://www.space.com/42621-tiny-satellites-offer-opportunities-and-threats.html>

Bombardelli, C., Merino-Martínez, M., Galilea, E. A., Peláez, J., Urrutxua, H., Herrera-Montojo, J., & Ander Iturri-Torrea, A. (2011, July 11). Ariadna Call for Ideas: Active Removal of Space Debris Ion Beam Shepherd for Contactless Debris Removal. European Space Agency. https://www.esa.int/gsp/ACT/doc/ARI/ARI%20Study%20Report/ACT-RPT-MAD-ARI-10-6411c-1107-FR-Ariadna-Ion_Beam_Shepherd_Madrid_4000101447.pdf

Boyle, A. (2019, June 13). Satellite consultant outlines a way-out plan to turn space junk into lunar treasure. GeekWire. <https://www.geekwire.com/2019/satellite-consultant-orbital-junk-moon/>

Bridenstine, J. (2019, December 4). Charter of the National Space Council Users' Advisory Group. National Aeronautics and Space Administration.
https://www.nasa.gov/sites/default/files/atoms/files/national_space_council_users_advisory_group_-_charter.pdf

Business Insider. (n. d.). Billionaires plan to launch tens of thousands of new satellites. Experts are working hard to ensure this doesn't lead to a disaster that ends human access to orbit.
<https://www.businessinsider.com/space-junk-kessler-syndrome-chain-reaction-prevention-2018-3>

Butts, M. (2013, September 17). Space Junk 3D: What goes up doesn't always come down.
<http://www.spacejunk3d.com/>

- CBC Digital Archives. (n. d.). 1978: Soviet nuclear satellite crashes in Canadian North. <https://www.cbc.ca/archives/entry/1978-soviet-nuclear-satellite-crashes-in-canadian-north>
- Chappell, B. (2019, April 2). NASA: Debris from India's anti-satellite test raised threat to space station. NPR. <https://www.npr.org/2019/04/02/709032198/nasa-debris-from-indias-anti-satellite-test-raised-threat-to-space-station>
- Chow, D. (2018, September 26). Space junk is a huge problem, but this high-tech satellite net just might help. Mach. <https://www.nbcnews.com/mach/science/space-junk-huge-problem-high-tech-satellite-net-just-might-ncna913426>
- David, L. (2019, April 21). A communications satellite just died in orbit. It's potentially dangerous space junk now. Space.com. <https://www.space.com/intelsat-29e-satellite-dead-space-junk.html>
- Dowd, K. (2020, March 27). OneWeb Files for Chapter 11 Restructuring to Execute Sale Process. OneWeb. <https://www.oneweb.world/media-center/oneweb-files-for-chapter-11-restructuring-to-execute-sale-process>
- European Space Agency. (2019, September 12). ESA commissions world's first space debris removal. https://www.esa.int/Safety_Security/Clean_Space/ESA_commissions_world_s_first_space_debris_removal
- European Space Agency. (2017, March 18). Space debris 2017 - a journey to Earth. http://www.esa.int/ESA_Multimedia/Videos/2017/04/Space_debris_2017_-_a_journey_to_Earth
- European Space Agency. (2013, April 24). 2013 space debris. https://www.esa.int/ESA_Multimedia/Videos/2013/04/Space_debris_2013
- Federal Communications Commission. (2020, April 2). Mitigation of Orbital Debris in the New Space Age. <https://docs.fcc.gov/public/attachments/DOC-363486A1.pdf>
- Federal Communications Commission. (2004, June 21). Second Report and Order. <https://docs.fcc.gov/public/attachments/FCC-04-130A1.pdf>
- Finkleman, D. (2015, August 3). 25-year orbital disposal guideline poorly cast. SpaceNews. <https://spacenews.com/letter-25-year-orbit-disposal-guideline-poorly-cast/>
- Garcia, M. (2017, August 7). Space debris and human spacecraft. National Aeronautics and Space Administration. https://www.nasa.gov/mission_pages/station/news/orbital_debris.html

- Gohd, C. (2020, April 16). Russia tests anti-satellite missile and the US Space Force is not happy. Space.com. https://www.space.com/russia-anti-satellite-missile-test-2020.html?utm_source=notification
- Gohd, C. (2020, April 20). No, they're not aliens – SpaceX's Starlink satellites surprise British skywatchers. Space.com. <https://www.space.com/spacex-starlink-satellites-surprise-british-skywatchers.html>
- Hitchins, T. (2019, September 24). New space debris rules stalled by year-long interagency spat. Breaking Defense. <https://breakingdefense.com/2019/09/new-space-debris-rules-stalled-by-year-long-interagency-spat/>
- Hitchins, T. (2019, December 9). US tightens space debris standards; Keeps 25-year cap. Breaking Defense. <https://breakingdefense.com/2019/12/us-tightens-space-debris-standards-keeps-25-year-cap/>
- Ialorek. (2020, January 28). Dealing with space junk and managing space traffic is the focus of UT Austin conference. <http://siliconhillsnews.com/2020/01/28/dealing-with-space-junk-and-managing-space-traffic-is-the-focus-of-ut-austin-conference/>
- Iannota, B. (2009, February 11). U.S. satellite destroyed in space collision. SpaceNews. <https://spacenews.com/u-s-satellite-destroyed-in-space-collision/>
- Inter-Agency Space Debris Coordination Committee. (2007, September). IADC space debris mitigation guidelines. https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf
- Jah, M. (n. d.). ASTRIAGraph compliance. University of Texas at Austin. <http://astria.tacc.utexas.edu/compliance>
- Jah, M. (2017, July 13). Statement of Dr. Moriba K. Jah The University of Texas at Austin to the Committee on Commerce, Science, and Transportation Subcommittee on Space, Science, and Competitiveness United States Senate on Reopening the American Frontier: Promoting Partnerships Between Commercial Space and the U.S. Government to Advance Exploration and Settlement. <https://sites.utexas.edu/moriba/files/2017/07/dr-moriba-jah-testimony-1-.pdf>
- Jasper, L. (2010) Open-Loop Thrust Profile Development for Tethered Towing of Large Space Objects. Ph.D. thesis provided by the author. University of Colorado, Boulder. Ph. D. thesis provided by the author.
- Keeter, B., & Dunbar, B. (2019, July 1). Space debris. National Aeronautics and Space Administration. https://www.nasa.gov/centers/hq/library/find/bibliographies/space_debris
- Kelso, T. S. (n. d.). Celestrak. <https://celestrak.com/>

- Kharpal, A. (2020, February 16). Space companies are racing to beam web access to the entire planet. But “space junk” is a big worry. <https://www.cnn.com/2020/02/17/space-junk-raise-concerns-as-more-and-more-satellites-are-launched.html>
- Knapp, A. (2013, January 27). Scientists build a working tractor beam. *Forbes*. <https://www.forbes.com/sites/alexknapp/2013/01/27/scientists-build-a-working-tractor-beam/#48edc24b725f>
- Krishna, S. (2019, December 26). The year of the satellite megaconstellation. *Slate*. <https://slate.com/technology/2019/12/space-satellite-constellations-spacex-starlink-junk.html>
- Langdon, D. (2018, October 3). How NASA is solving the space junk problem. *Innovation & Tech Today*. <https://innotechtoday.com/how-nasa-is-solving-the-space-junk-problem/>
- LeoLabs. (n. d.). <https://www.leolabs.space/>
- Letzer, R. (2018, October 19). This hunk of metal fell from space and landed in California. *Space.com*. <https://www.space.com/42204-space-debris-object-california.html>
- Liou, J.-C. (n. d.). Effectiveness of Satellite Postmission Disposal To Limit Orbital Debris Population Growth in Low Earth Orbit. <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150003819.pdf>
- National Aeronautics and Space Administration. (2018, June). NanoRacks-Remove Debris. https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=7350
- National Aeronautics and Space Administration. (2019, October 10). NASA’s Earth observing system. <https://eospsa.nasa.gov/content/nasas-earth-observing-system-project-science-office>
- National Aeronautics and Space Administration. (2019, April 25). Process for limiting orbital debris. Office of Safety and Mission Assurance. <https://standards.nasa.gov/standard/nasa/nasa-std-871914>
- National Aeronautics and Space Administration. (2015). A Research Guide to International Space Station: Environmental Effects, https://www.nasa.gov/sites/default/files/files/NP-2015-03-015-JSC_Space_Environment-ISS-Mini-Book-2015-508.pdf
- National Aeronautics and Space Administration. (n. d.). Space debris. https://www.nasa.gov/centers/hq/library/find/bibliographies/space_debris
- National Aeronautics and Space Administration. (2013, September 26). Space debris and human spacecraft. https://www.nasa.gov/mission_pages/station/news/orbital_debris.html

- National Aeronautics and Space Administration. (2014, February 12). What is a satellite? <https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-a-satellite-58.html>
- National Oceanic and Atmospheric Administration. (2018, January 19). Does space junk fall from the sky? <https://www.nesdis.noaa.gov/content/does-space-junk-fall-sky>
- Nelson, J. W. (2018, November 19). Lost in space? Gaps in the international space object regime. Blog of the European Journal of International Law. <https://www.ejiltalk.org/lost-in-space-gaps-in-the-international-space-object-registration-regime/>
- Pappas, S. (2017, March 30). Rugged Antarctica shows its ice in new 3D map. Space.com. <https://www.space.com/36271-3d-map-of-antarctica-ice.html>
- Pappas, S. (2019, January 30). This “empty trash bag” is orbiting Earth in a very strange way. Space.com. <https://www.space.com/43178-empty-trash-bag-space-debris.html>
- Parsons, J. (2020, April 24). What are Elon Musk’s Starlink satellites and how do they work? Metro. <https://metro.co.uk/2020/04/24/starlink-satellites-work-12604227/?ito=cbshare>
- Pultarova, T. (2017, April 26). Meet the space custodians: Debris cleanup plans emerge. <https://www.space.com/36602-space-junk-cleanup-concepts.html>
- Rosengren, A. (2020, February 4). An astrodynamist’s take on satellite mega-constellations. LinkedIn. <https://www.linkedin.com/pulse/astrodynamicists-take-satellite-mega-constellations-aaron-rosengren/>
- Rosengren, A. J., Alessi, E. M., Rossi, A., & Valsecchi, G. B. Chaos in navigation satellite orbits caused by the perturbed motion of the moon. Monthly Notices of the Royal Astronomical Society, 449, 3522–3526. Paper provided by the first author. <https://academic.oup.com/mnras/article/449/4/3522/1184971>
- Schaub, H., Jasper, L., Anderson, P. V., & McKnight, D. S. (2013, February 15). Cost and risk assessment for spacecraft operation decisions caused by the space debris environment. Preprint submitted to Acta Astronautica. Paper provided by second author.
- Space Safety Coalition. (2019, September 16). Best Practices for the Sustainability of Space Operations. https://spacesafety.org/wp-content/uploads/2020/02/Endorsement-of-Best-Practices-for-Sustainability_v30.pdf
- Space-Track.org. (n. d.). <https://www.space-track.org/auth/login>
- Staughton, J. (2020, February 2). How does space debris impact Earth’s environment and atmosphere? ScienceABC. <https://www.scienceabc.com/nature/universe/how-does-space-debris-impact-earths-environment-and-atmosphere.html>

Stuff in Space. (n. d.). <http://stuffin.space/>

The White House. (2018, June 18). Space Policy Directive-3, National Space Traffic Management Policy. <https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/>

The White House. (2020, April 6). Executive Order on Encouraging International Support for the Recovery and Use of Space Resources. <https://www.whitehouse.gov/presidential-actions/executive-order-encouraging-international-support-recovery-use-space-resources/>

Union of Concerned Scientists. (2019, December 6). UCS satellite database. <https://www.ucsusa.org/resources/satellite-database>

United Nations Office of Outer Space Affairs. (n. d.). Online index of objects launched into outer space. https://www.unoosa.org/oosa/osoindex/search-ng.jsp?lf_id=

United Nations Office of Outer Space Affairs. (n. d.). Convention on international liability caused by space objects. Resolution adopted by the General Assembly 2777 (XXVI). https://www.unoosa.org/pdf/gares/ARES_26_2777E.pdf

United Nations Office of Outer Space Affairs. (n. d.). Convention on registration of objects launched into outer space. Resolution adopted by the General Assembly 3235 (XXIX). <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/registration-convention.html>

U.S. Government Orbital Debris Mitigation Standard Practices, (2019, November, update). https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

Verbeek, D., & Fouquet, H. (2020, January 30). Can we get to space without damaging the Earth through huge carbon emissions? Los Angeles Times. <https://www.latimes.com/business/story/2020-01-30/space-launch-carbon-emissions>

Wall, M. (2019, April 24). Meet OSCaR: Tiny cubesat would clean up space junk. Space.com. <https://www.space.com/space-junk-cleanup-cubesat-oscar.html>

Wei-Haas, M. (2019, April 25). Space junk is a huge problem—and it's only getting bigger. National Geographic. <https://www.nationalgeographic.com/science/space/reference/space-junk/#close>

Weisberger, M. (2019, April 17). Rocket stage launched 10 years ago disintegrates into trail of space junk. Space.com. <https://www.space.com/atlas-v-rocket-debris-video.html>

Weiss, G. W. (2008, Sep. 26). The life and death of Cosmos 954. Central Intelligence Agency. <https://www.cia.gov/library/readingroom/docs/CIA-RDP85B01152R000200260006-4.pdf>

Williams, M. (2017, January 6). What is low earth orbit? Universetoday.com.
<https://www.universetoday.com/85322/what-is-low-earth-orbit/>

Witze, A. (2018, September 5). The quest to conquer Earth's space junk problem. Nature.
<https://www.nature.com/articles/d41586-018-06170-1>