SATELLITES

Thesis Project

Final Version
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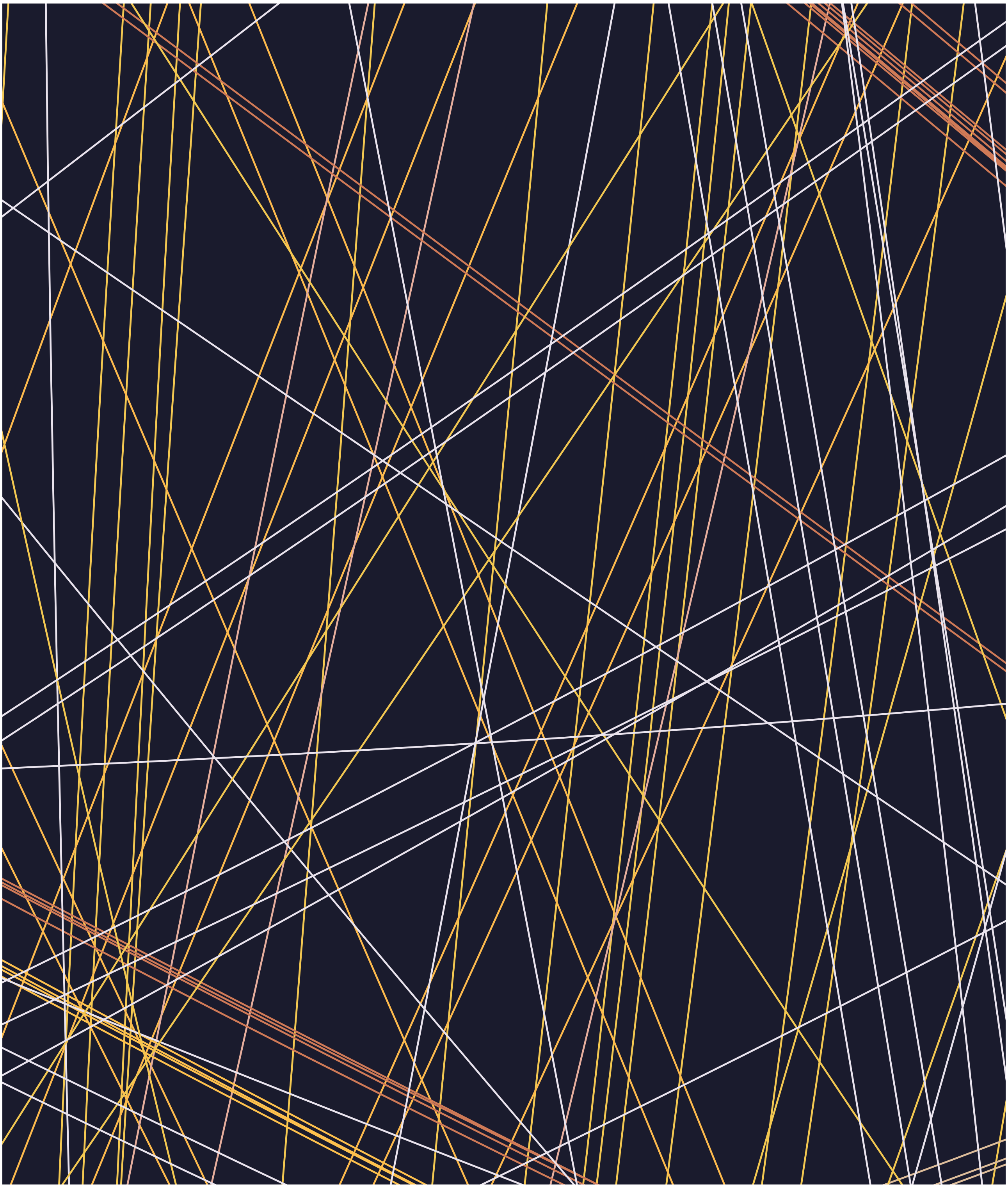


SATELLITES

Thesis Project

WILL MANNING **MAY 31, 2021**

THESIS PRESENTED IN PARTIAL FULFILLMENT
OF REQUIREMENTS FOR THE MASTER OF FINE ARTS DEGREE

MASSEY UNIVERSITY
WELLINGTON, NEW ZEALAND

A strong, heartfelt thank you to my supervisors, Anna Brown and Brian Lucid, for their support, guidance, and input throughout this project. Special thanks to Julieanna Preston, whose tireless effort and endless generosity –especially when the chips were down– has inspired me to continue on to the end of this program. Thank you to Jason O'Hara, Finn Chadwick, Paora Allen, Warren Maxwell, and all the other professors, staff, and students for their thoughtful feedback during critiques and prototypes of this and other projects at Massey. I'd also like to thank Lee Leighton for her efforts in helping to source and negotiate printing for this and other projects of mine at Massey. She's the best in the business, and without her help I wouldn't have a thesis to present at all. And finally, a shout out to my cat, Yogi, who has napped in front of the computer every day I've worked on this thesis, snoozing softly and providing supportive purrs.

CONTENTS

"Space is critical to all nations and our way of life. The demands on space systems continue in this time of crisis where global logistics, transportation and communication are key to defeating the COVID-19 pandemic."

—Gen. John Raymond, USAF Chief of Space Operations, 2020

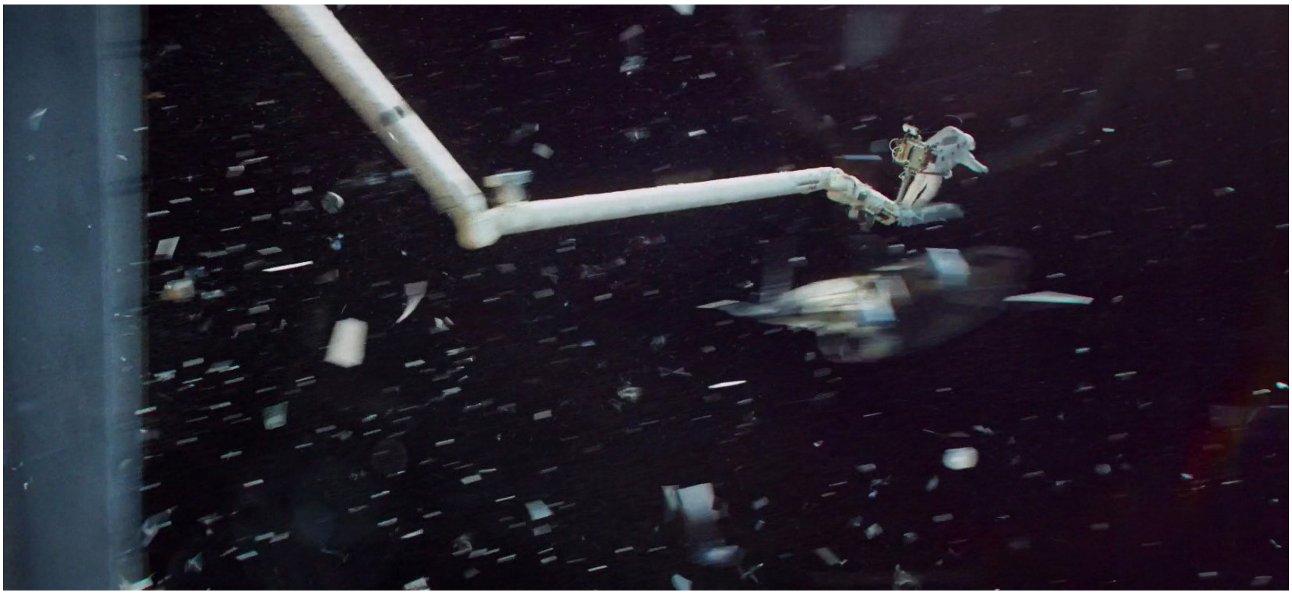
Introduction

In the 2013 motion picture *Gravity*, starring Sandra Bullock and George Clooney, a spy satellite is shot down by a missile, while the two main characters are in space. This causes the accidental and violent destruction of nearly all satellites orbiting earth,[1] as debris from the destroyed spy satellite crashes into other nearby satellites, which create more debris, and so on. While the film is science fiction, and many of the science elements of the film have been criticized in the media, one thing most could agree on was that a similar scenario actually occurring is entirely possible.[2]

In fact, the possibility of the kind of collisional cascading portrayed in *Gravity* was first proposed in 1978 by NASA scientist Donald J. Kessler. And as modern life has become ever more reliant on technology and instant communication, so too have we become increasingly vulnerable to such an event – the end result of which could render certain Earth orbits unusable, up to and including our ability access to space, for centuries.

This thesis approaches the problem of satellite overpopulation, and the seemingly inevitable cataclysmic destruction of satellites, by merging science communication and data visualization techniques with art and design. This thesis project explores the orbital data of the first and second instances of unintentional satellite collisions and their debris fields, presenting them as a sort of time capsule for future generations who must live with the consequences of our proliferation of Earth orbit.

It is the goal of this project to draw attention to the vast enormousness of the problem by illustrating the omnipresence of space debris, and to inspire further interest in the prevention and mitigation of space junk. As the COVID-19 pandemic, which began during the middle of the research for this thesis, has made clear: modern civilization is increasingly dependent on the Internet, mobile phones, and ubiquitous connectivity.



1 Cuarón, A. (Director). (2013). *Gravity* [Motion picture]. United States: Warner Bros. Pictures.
2 Dewey, C. (2013, October 21). Here's what 'Gravity' gets right and wrong about space. Retrieved from https://www.washingtonpost.com/news/wonk/wp/2013/10/21/heres-what-gravity-gets-right-and-wrong-about-space/

Fig. 1-3:

Screenshots of satellite debris strike on the fictional Space Shuttle 'Explorer,' and the Hubble Space Telescope. Separately, debris strikes on the International Space Station and Russian Soyuz spacecraft. Source: Cuarón, A. (Director). (2013). *Gravity* [Motion picture]. United States: Warner Bros. Pictures.

SECTION I: WHAT YOU NEED TO KNOW

Basic science background information

In the 1970s, the North American Aerospace Defense Command (NORAD) made satellite orbit data available to the public. Studying the formation and behavior of asteroid belts, NASA scientist Donald Kessler applied his mathematical models to the newly released database of man made satellites. In so doing, he along with fellow NASA scientist Burton Cour-Palais, predicted the inevitable cascade of satellite collisions and subsequent debris field that would one day envelop the Earth if humans continue placing more and more satellites into orbit.[3] This collisional cascading scenario is known today as 'Kessler Syndrome,' and as the decades have gone by and technology has advanced, its likelihood has ever increased – as has the severity of the consequences for life on Earth.

The likelihood of a Kessler Syndrome event occurring is not disputed in the scientific community.[4] However, methods for mitigating the consequences, or what those consequences may be, is an area of active research by scientists around the world. Much of what might or could happen depends on the exact nature of the collisional cascading, and how widespread it may be.

One such example used to illustrate the direness of the problem occurred in 1998, when the Panamsat communications satellite, Galaxy 4, experienced a malfunction leading to the loss of pager service across North America – known colloquially as the *Great Pager Blackout of 1998*.[5,6] This event highlighted the vulnerabilities of modern communications networks, and demonstrated the impact of the loss of a single satellite. Should a Kessler syndrome event occur, tens or hundreds of satellites could be destroyed at once.

Fig. 4:

Boeing 601 Satellite, the same model as the Panamsat Galaxy 4. Source: Boeing. (n.d.). *Boeing 601* [Rendering]. Retrieved from https://www.boeing.com/history/products/601-satellite.page

According to the Union of Concerned Scientists,[7] there are currently around 2,700 active satellites orbiting the Earth with an additional estimated 3,000 or so dead satellites in Earth Orbit. However, not all of these satellites are physically close to one another.

Earth Orbit is divided into three main bands based on the altitudes they cover: Low Earth Orbit (LEO), below 2,000km; Medium Earth Orbit (MEO), 2,000–35,786km; and High Earth Orbit (HEO), from 35,786km and beyond.[8] Satellites placed LEO constitute the bulk of all man-made satellites in orbit, and are mostly low-latency communication satellites, scientific monitoring satellites, and satellites used in precision agriculture. The MEO band is where Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) satellites are placed. HEO satellites tend to be weather monitoring satellites and higher latency communications satellites for phone and television.

3 Kessler, D. J., & Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research, 83(A6), 2637.* doi:10.1029/ja083ia06p02637
4 Kessler, D. J., Johnson, N. L., Liou, J. C., Matney, M., & McQuerry, S. C. (2010). The Kessler Syndrome: Implications to Future Space Operations (AAS 10-016). In *33rd, Rocky Mountain Guidance and Control Conference* (p. 16). Breckenridge, CO: American Astronautical Society
5 Kaplan, K. (1998, May 21). Outer space outage signals growing dependence on satellites. Retrieved from https://www.latimes.com/archives/la-xpm-1998-may-21-mn-52190-story.html
6 Zuckerman, L. (1998, May 21). Satellite failure is rare, and therefore unsettling. Retrieved from https://www.nytimes.com/1998/05/21/business/satellite-failure-is-rare-and-therefore-unsettling.html
7 Union of Concerned Scientists. (n.d.). UCS satellite database. Retrieved December 10, 2020, from https://www.ucsusa.org/resources/satellite-databas
8 Riebeek, H., & Simmon, R. (2009, September 4). Catalog of earth satellite orbits. Retrieved from NASA Earth Observatory website: https://earthobservatory.nasa.gov/features/OrbitsCatalog

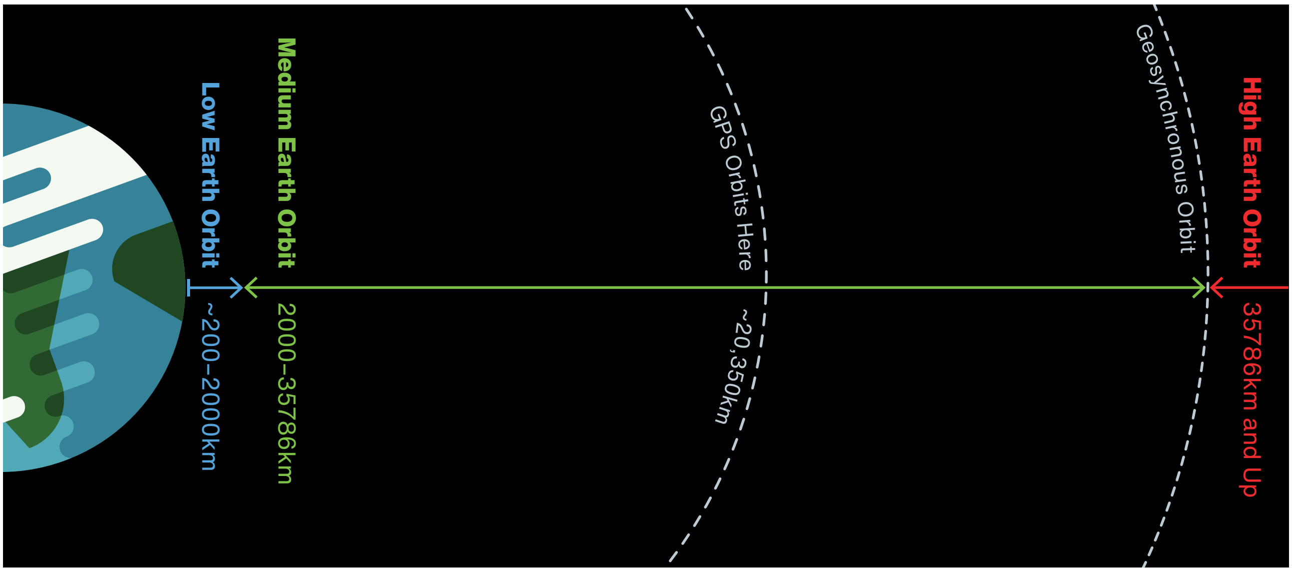


Fig. 5:

Diagram showing the relative size and placement of Earth orbits.

There are an additional two commonly used orbits of note: geosynchronous orbit, and Molniya orbit. Geosynchronous Orbit (GEO), where satellites orbit at the exact same speed as Earth's rotation thereby hovering stationary over a single place, is at 35,786km above the surface. This also serves as the border between MEO and HEO. A Molniya orbit, invented by the Soviet Union to deliver satellite communications to higher latitudes of the Earth, is a highly elliptical orbit which transcends LEO, MEO, and sometimes HEO.[8] Approximately 14,000 objects greater than 10cm are currently tracked in LEO alone, while several million more smaller objects are thought to exist across Earth's orbit generally.[9]

With this basic information in mind, one can begin to speculate on the possible scenarios and subsequent consequences of a Kessler event. More alarming still is the rapid increase in satellite launches, and plans for future launches, most notably SpaceX's Starlink satellite Internet constellation which is meant to consist of 12,000 satellites by the mid-2020's.[10] As more and more satellites are launched into orbit, along with more and more rocket parts that were used to get them there fill our skies, the likelihood of a catastrophic Kessler event increases. While some collisional cascades may only impact certain orbits, since the distance between most satellites is quite large, scenarios involving Molniya orbits have the risk of impacting on all Earth orbits as Molniya satellites swing across multiple orbits at once. The loss of communication satellites in LEO, for instance, could have devastating economic and human consequences. However, the loss of LEO satellites and MEO satellites, wrought by debris in a Molniya orbit, has the potential to end, even if only temporarily, modern civilization as we know it.

9 ESA. (2020). *Space Environment Report* (GEN-DB-LOG-00288-OPS-SD).
Retrieved from European Space Agency website: https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf
10 Drake, N. (2019, May 29). Will SpaceX's Starlink satellites harm astronomy? Here's what we know.
Retrieved from https://www.nationalgeographic.com/science/article/elon-musk-starlink-internet-satellites-trouble-for-astronomy-light-pollution

At the height of the cold war's satellite technology race, the United States and the Soviet Union tested various methods of satellite destruction, fearing that one would use their satellites to attack the other. In September 1985, the United States successfully attacked and destroyed the first satellite in orbit during a planned test of the then-new Vought ASM-135A Anti-Satellite Missile.[11,12] The target of the test was the United States' own Solwind P78-1, a solar observation satellite which had experienced irreparable malfunctions and was no longer usable at the time.[11] The destruction was well-planned to minimize debris, creating only 285 pieces of trackable debris, the last of which burned up on re-entry into the atmosphere by 2008.[13]

On January 11, 2007, the Chinese government conducted the world's second successful Anti-Satellite Missile (ASAT) test, which resulted in the destruction of the Fengyun-1C weather satellite, which orbited at an altitude of 850km – about 300km higher than Solwind P78-1.[11,14] The destruction of the Fengyun-1C resulted in the creation of around 4,000 pieces of trackable debris, and an estimated 40,000 pieces of untrackable debris (smaller than 10cm in diameter).[11]

The debris from these destroyed satellites only adds to the problem of space junk orbiting the Earth. According to the US Space Force's SatCat database,[15] about 620 rocket bodies currently orbit the Earth. Aside from collisions with other pieces of debris, many of these rocket stages contain leftover fuel or batteries which could explode,[16] creating further debris or damaging other satellites or spacecraft, and increasing the likelihood of a Kessler event.

Fig. 6:

Replica model of a Fengyun Type 2 satellite, similar to the Fengyun-1C, at the Shanghai Museum of Science & Technology. Source: Hałun, J. (2009, August 29). *Model of Fengyun-2 satellite* [Photograph]. Retrieved from https://en.wikipedia.org/wiki/Fengyun#/media/File:20090829_Model_of_Fengyun-2_4002.JPG

11 United States Air Force. (2016, March 14). *Vought ASM-135A anti-satellite missile.* Retrieved from https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/198034/asm-135-asat/
12 Grego, L. (2012). *A History of Anti-Satellite Programs.* Retrieved from Union of Concerned Scientists website: https://www.ucsusa.org/sites/default/files/2019-09/a-history-of-ASAT-programs_lo-res.pdf
13 NASA. (2008). *History of On-Orbit Satellite Fragmentations* (14th Edition). Retrieved from Orbital Debris Program Office website: https://orbitaldebris.jsc.nasa.gov/library/satellitefraghistory/tm-2008-214779.pdf
14 Harvard University. (2018, September). *Fengyun-1C Debris Cloud Evolution Over One Decade.* Paper presented at Advanced Maui Optical and Space Surveillance Technologies Conference, Hawaii. Retrieved from https://ui.adsabs.harvard.edu/abs/2018amos.confE..50L/abstract
15 USSF, & SAIC. (2021). SATCAT [Database]. Retrieved from United States Space Force, 18th Space Control Squadron website: https://www.space-track.org
16 Foust, J. (2020, October 13). Upper stages top list of most dangerous space debris. Retrieved from https://spacenews.com/upper-stages-top-list-of-most-dangerous-space-debris/

Fig. 7

F-15 Eagle aircraft firing the Vought ASM-135A missile which destroyed Solwind P78-1 in 1985. Source: US National Archives. (1985). *An air-to-air left side view of an F-15 Eagle aircraft releasing an anti-satellite (ASAT) missile during a test* [Photograph]. Retrieved from https://catalog.archives.gov/id/6426035

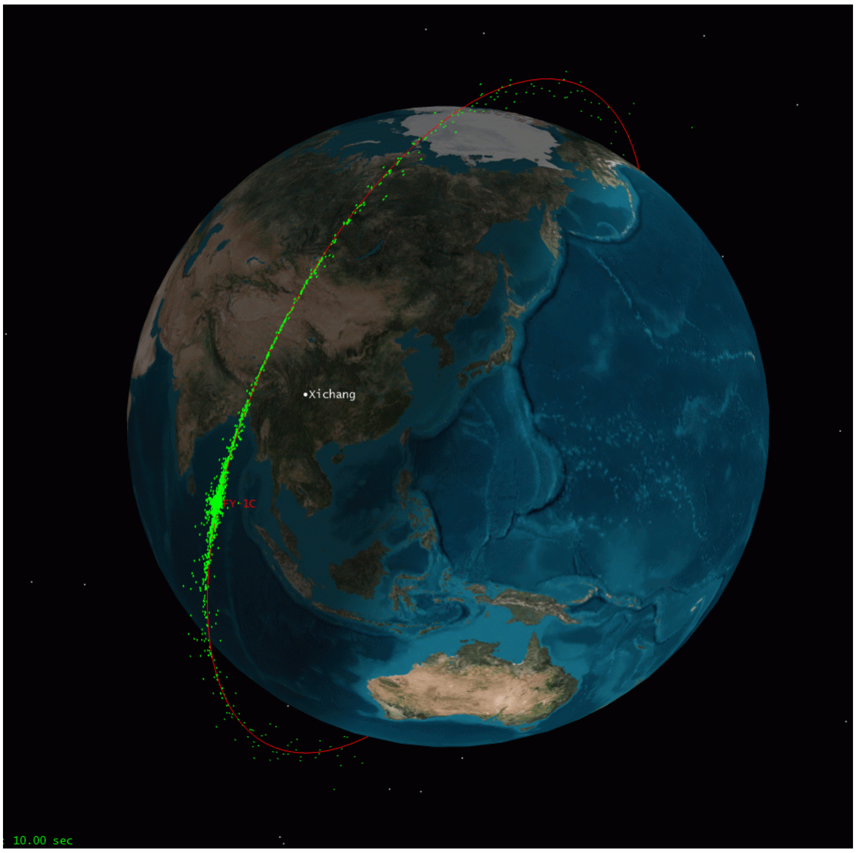


Fig. 8

Debris field (green) of Fengyun-1C satellite approximately 5 minutes after destruction on January 11, 2007. Source: CelesTrak. (2012, June 22). *STK Viewer file of Chinese ASAT scenario* [Screenshot]. Retrieved from http://www.celestrak.com/events/asat.php

On the morning of February 10, 2009, about 790km above Northern Siberia, a privately owned U.S. communications satellite known as Iridium-33 collided with a defunct Russian satellite known as Cosmos-2251.[17] Each satellite weighed about 800kg, and were traveling at speeds of around 36,000kph, when they collided. This event was the first ever recorded hypervelocity collision between two satellites in orbit.

Iridium-33 was a 560kg LM700 series satellite, designed and built by Lockheed Martin and Motorola for Iridium Communications and launched into orbit in 1997.[17,18,19] The satellite was part of the Iridium constellation, which provides satellite telephone services to customers on the ground. Cosmos-2251 was a 900kg retired Strela 2 (Стрела 2) military communications satellite, which was developed by the Soviet Union in the 1970s and designed to have a service life of 5 years.[17,18,19] This particular one was launched in 1993, and was therefore non-operational at the time of collision.

Within about three hours of collision, the debris field stretched around the world, following both satellite's orbital planes, and began spreading outwards. Within a year, debris from the collision covered the entire globe. It is estimated that the impact created roughly 2,000 pieces of trackable debris (larger than 10cm in diameter), equal to about 10% of all objects in Earth orbit at the time.[17,19] It is likely that the collision created many more pieces of debris that were too small to track or detect.

In 2020, it is estimated that about 75% of all debris originating from the Cosmos-Iridium collision will have re-entered Earth's atmosphere, burning up along the way.[17,19] The remaining quarter of this debris cloud will likely remain in orbit, and continue to pose a hazard to satellites and space travel, for the next 80–100 years.[17,19] In some respects, the Cosmos-Iridium collision represents the first instance of Kessler Syndrome occurring. Unless the number of satellites and other objects orbiting the Earth can be reduced, the number of future accidental collisions is certain.

Fig. 5:

Original prototype of the LM700 satellite, the same model as Iridium-33. Source: Smithsonian Institution, National Air and Space Museum. (n.d.). *Communications Satellite, Iridium* [Photograph]. Retrieved from http://n2t.net/ark:/65665/nv9a33c5480-0c66-4e41-beb7-ace4f4e4f384

17 NASA, & Nicholas, J. (2009, October). *The Collision of Iridium 33 and Cosmos 2251: The Shape of Things to Come.* Paper presented at 60th International Astronautical Congress, Daejeon, South Korea. Retrieved from NASA Technical Reports Server: https://ntrs.nasa.gov/citations/20100002023
18 Weeden, B. (2010). 2009 Iridium-Cosmos Collision Fact Sheet. Retrieved from Secure World Foundation website: https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf
19 Tan, A., Zhang, T. X., & Dokhanian, M. (2013). Analysis of the Iridium 33 and Cosmos 2251 Collision using Velocity Perturbations of the Fragments. Advances in Aerospace Science and Applications, 3(1), 13-25. doi:10.1080/08929882.2010.493078

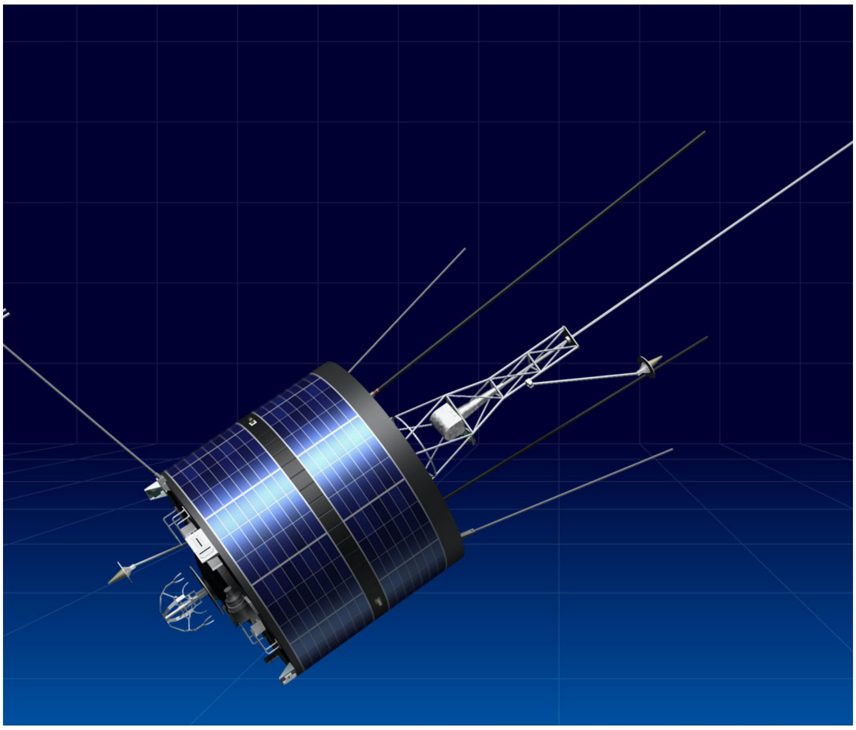


Fig. 6:

Rendering of the Strela-2M (Стрела-2M), the same model as Cosmos-2251. Source: ISS-Reshetnev Company. (n.d.). *Космический аппарат Стрела*-2M [Rendering]. Retrieved from http://www.iss-reshetnev.ru/spacecraft/spacecraft-communications/strela-2m

Fig. 7:

Satellite flare of Iridium-33 from April 2007. Satellite flares occur when sunlight is reflected off solar panels or other large reflective surfaces. Source: Tough, A. (2007, April 28). *Flare from Iridium 33* [Photograph]. Retrieved from https://www.flickr.com/photos/143301583@N07/29940602211/

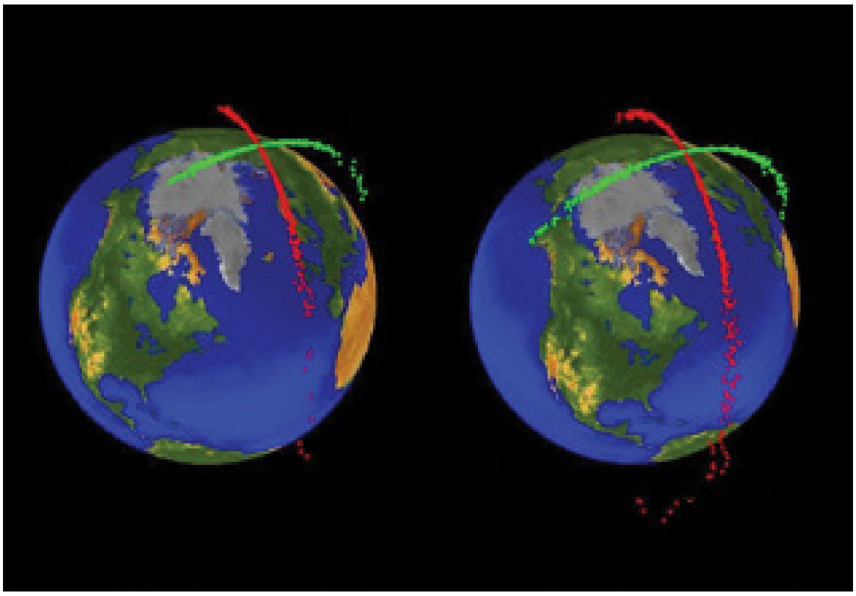


Fig. 8:

Initial spread of trackable debris from Iridium-33 and Cosmos-2251. Debris is shown at 1 hour from impact at left, and 2 hours from impact at right. Source: NASA, & Nicholas, J. (2009, October). *The Collision of Iridium 33 and Cosmos 2251: The Shape of Things to Come.* Paper presented at 60th International Astronautical Congress, Daejeon, South Korea. Retrieved from NASA Technical Reports Server: https://ntrs.nasa.gov/citations/20100002023

SECTION II: WHAT YOU ARE LOOKING AT

The posters and their meaning

POSTER I: Trackable Iridium-33 and Cosmos-2251 Debris Paths

The first poster in the series shows two sets of orbital debris paths over New Zealand, from the Iridium/ Cosmos satellite collision. These paths represent all known, trackable debris fragments >10cm in size. It takes ~90 minutes for these debris to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of debris passing overhead.

POSTER II: Trackable Fengyun-1C Debris Paths

The second poster in the series shows one set of orbital debris paths over New Zealand from the Fengyun-1C satellite. These paths represent all known, trackable debris fragments >10cm in size. It takes ~90 minutes for these debris to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of debris passing overhead.

POSTER III: Starlink Satellite Paths

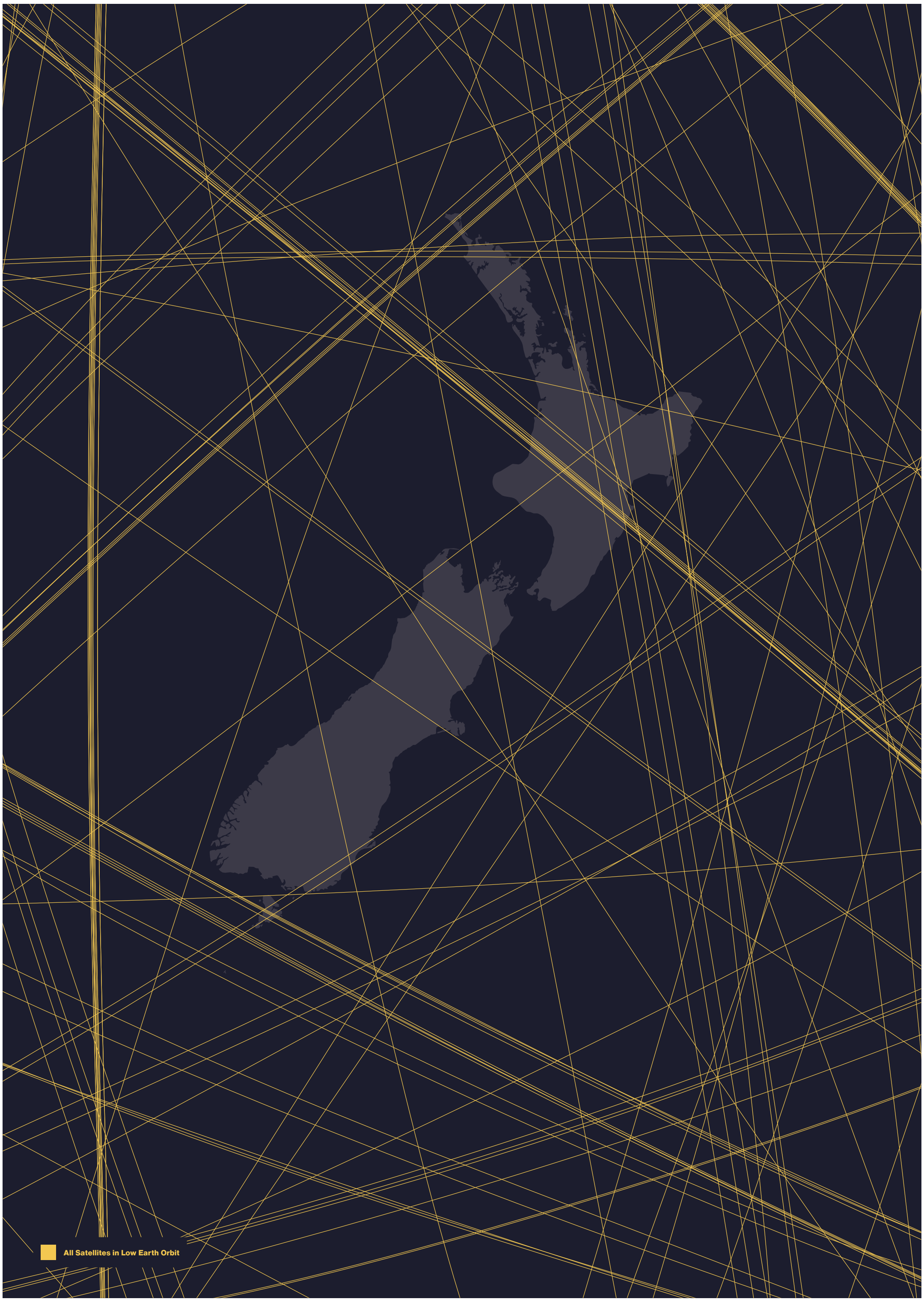
The third poster in the series shows orbital paths of all Starlink satellites launched in the first quarter of 2021. It takes ~90 minutes for these satellites to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of satellites passing overhead.

POSTER IV: Trackable Dead Rocket Bodies

The fourth poster in the series shows one set of orbital debris paths over New Zealand from spent rocket bodies. These paths represent all known rocket bodies captured in Low Earth Orbit. It takes ~90 minutes for these debris to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of debris passing overhead.

POSTER V: All Other Active Satellites and Debris Paths In Low Earth Orbit

The fifth poster in the series shows all other satellite debris ,and all other active satellites, which aren't featured in the previous posters. These orbital paths are limited only to objects in Low Earth Orbit, and only to objects of a trackable size >10cm. It takes ~90 minutes for these objects to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of objects passing overhead.

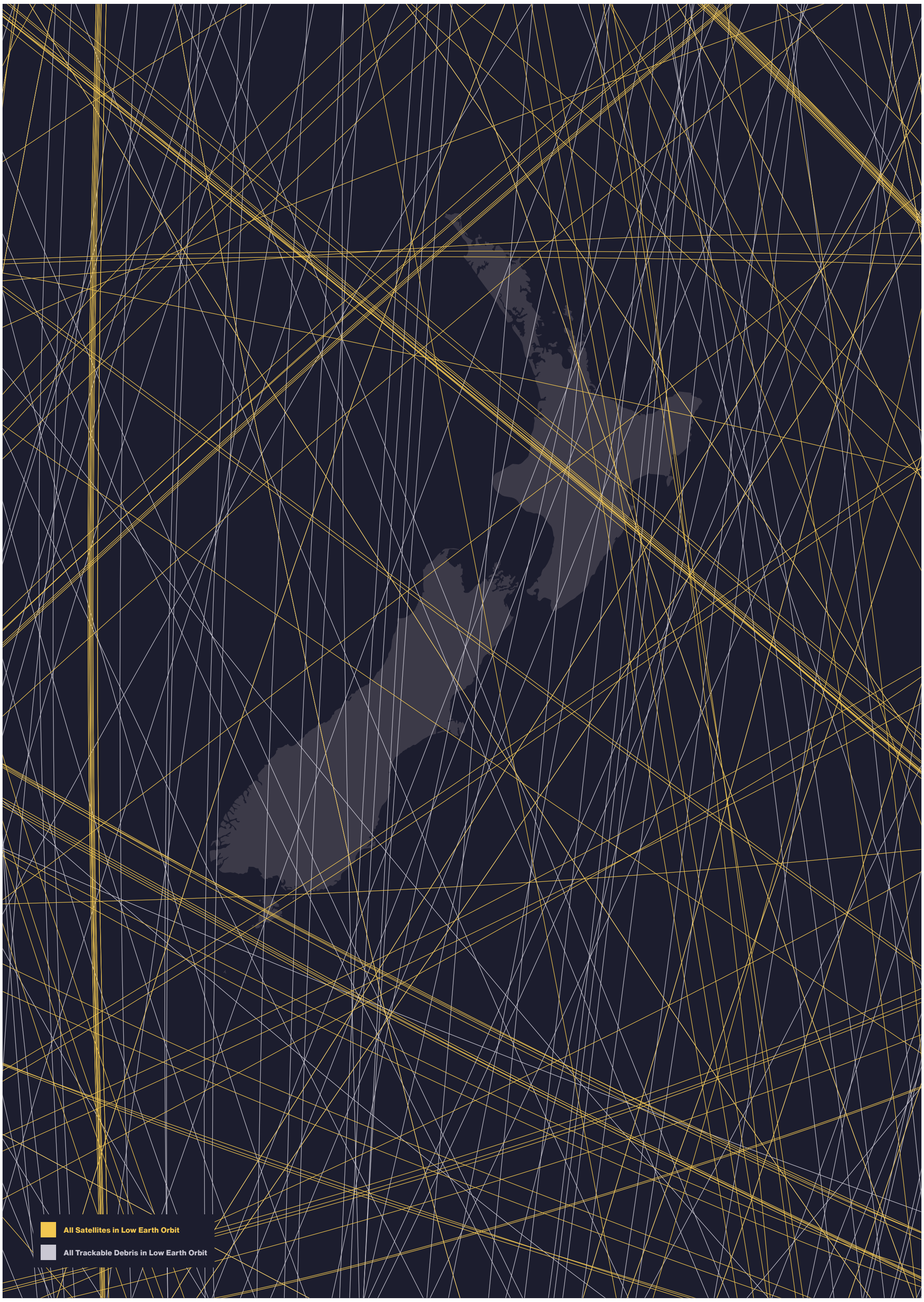


POSTER VI: All Active Satellite Paths In Low Earth Orbit Combined

The sixth poster in the series shows a complete set of all orbits for all known satellites currently in Low Earth Orbit (LEO). It takes ~90 minutes for most satellites in LEO to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of satellites passing overhead.

POSTER VII: All Trackable Debris Paths In Low Earth Orbit

The seventh poster in the series shows a complete set of all orbits for all known, trackable debris (>10cm in size) currently in Low Earth Orbit (LEO). It takes ~90 minutes for most objects in LEO to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of debris passing overhead.



POSTER VII: All Trackable Object Paths In Low Earth Orbit

The eighth poster in the series shows a complete set of all orbits for all known, trackable objects currently in Low Earth Orbit (LEO). It takes ~90 minutes for most objects in LEO to make a complete orbit around the Earth, therefore these paths represent ~90 minutes of objects passing overhead.

SECTION III: WHY YOU SHOULD CARE

Consequences of inaction

"Since the beginning of the space age, thousands of satellites have been placed in Earth orbit by various nations. Because many of these satellites are in orbits which cross one another, there is a finite probability of collisions between them. Satellite collisions will produce a number of fragments, some of which may be capable of fragmenting another satellite upon collision, creating even more fragments. The result would be an exponential increase in the number of objects with time, creating a belt of debris around the Earth."

—Donald J. Kessler and Burton G. Cour-Palais, NASA, 1978

In their original 1978 report to NASA, Don Kessler and Burton Cour-Palais predicted a 'debris belt' encircling the Earth.[20] At the time, the Global Positioning System (GPS) was strictly for use by the U.S. military, and wasn't made publicly available until 1983 – or made particularly useful until 2000, when restrictions on GPS accuracy were removed by President Clinton.[21] Since then the world has had twenty years to become increasingly reliant on GPS for everything from map apps on your smartphone, to banking, to power plant management, to air travel, to WiFi and more. Most of our modern civilization has become, in some way, dependent on GPS to function. Not to mention the ever increasing number of new satellites launched for mobile phone service, internet connectivity, meteorology, observation, and a slew of other activities. In short, a debris belt encircling the Earth is only one aspect of the civilization-crippling chaos that would be unleashed, should a Kessler Syndrome event occur and cascade out of control. With space debris traveling around the Earth at speeds in excess of 20,000kph (12,400mph),[22] even the smallest piece of debris has the potential to cripple, if not outright obliterate, most satellites. Reducing the number of satellites in space, in conjunction with finding ways to neutralize existing space debris, is the only real way to mitigate the risk posed by a runaway collisional cascade of space debris on satellites in orbit.

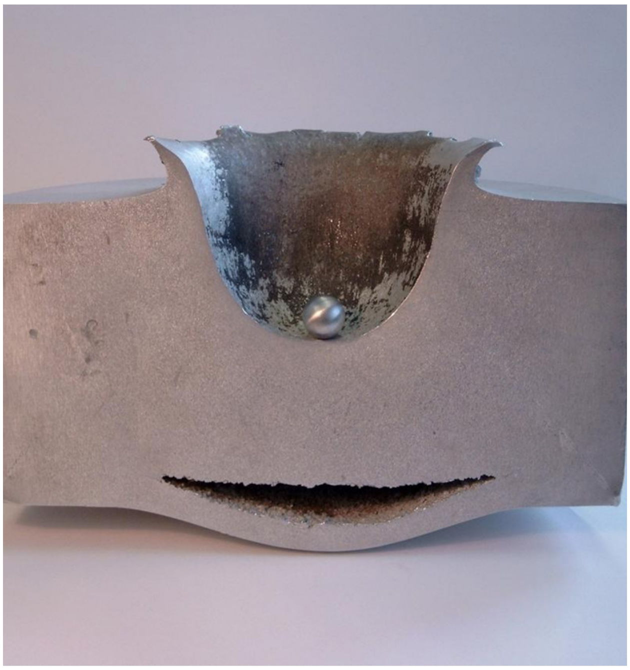


Fig. 9:

Hypervelocity impact test between a 1.7g sphere of aluminum traveling at approximately 6.8 km/second and a block of aluminum 18cm thick, simulating space debris impact on spacecraft in orbit. In such an impact, the pressure and temperature can exceed those found at the center of the Earth. Source: ESA. (2009, February 20). *Hypervelocity impact sample* [Photograph]. Retrieved from https://www.esa.int/ESA_Multimedia/Images/2009/02/Hypervelocity_impact_sample

20 Kessler, D. J., & Cour-Palais, B. G. (1978). *Collision frequency of artificial satellites: The creation of a debris belt. Journal of Geophysical Research, 83(A6), 2637.* doi:10.1029/ja083ia06p0263

21 National Coordination Office for Space-Based Positioning, Navigation, and Timing. (2018, September 27). GPS.gov: Selective availability. Retrieved from *https://www.gps.gov/systems/gps/modernization/sa/*

22 ESA. (2020). *Space Environment Report* (GEN-DB-LOG-00288-OPS-SD). Retrieved from European Space Agency website: https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

So, what would happen to life on Earth if some or all of our satellites were destroyed or disabled? Answering that question depends greatly on which Earth orbits are affected, and weather or not GPS or GLONASS (Global Navigation Satellite System) are disabled. An event affecting all orbits simultaneously would be incredibly rare, as high Earth orbits are sparsely populated. Nevertheless, it is useful to examine the worst-case scenario to understand the extent to which modern civilization is reliant on satellites. Likewise, in 1978 when Kessler Syndrome was first described, all Earth orbits were sparsely populated.

Let's assume such a worst-case scenario were to occur today, where a field of fast moving debris disables a majority of all satellites in all orbital planes. Within about 30 seconds, satellite phones, satellite TV, satellite Internet, and satellite radio all stop.[23,24] International news correspondents cut out due to loss of signal, broadcasts of international sports cease, and half of all TV channels go dark. Most modern aircraft flying through international airspace lose the ability to communicate with air traffic control. Ships at sea lose most communications, and search and rescue beacons stop working. Within one hour, international phone calls lose audio fidelity, and global Internet speeds begin to drop as communications are rerouted through undersea cables and ground networks.[23,24]

Up to this point these symptoms, while catastrophic in their own right, pale in comparison to what might happen if the GPS or GLONASS satellite constellations cease functioning. These systems both work in much the same way: each satellite is equipped with a highly accurate atomic clock, which transmits the time back to Earth. A device receiving signals from three or more of these satellites can calculate it's own position based on the transmission time (and transmitted time) of each.[25] Without these signals from GPS or GLONASS, the device must rely on it's much less accurate internal clock. Most conventional electromechanical clocks are able to maintain synchronized with each other for several minutes to several hours before drifting apart by fractions of a second, while commercially available but expensive Rubidium-based atomic clocks can remain synchronized with each other for about a day.[24,26] This minute difference in timekeeping by different clocks, known as clock drift, can have a profound impact on services and technologies which rely on hyper-accurate timing in order to function properly.

Since we have never completely lost GPS satellites before, in a global context exceeding one hour, it is impossible to say with certainty how long it would take before ground-based clocks drift apart. The time from initial loss of GPS satellites, until noticeable impacts on GPS reliant terrestrial technologies occur, is estimated to be within roughly 4-5 hours.[23,24,25] At this point, the crisis would swing into overdrive. Internet banking, bank transfers, ATMs, stock trades, and all manner of electronic financial transactions are no longer possible.[23,24] Traffic control systems fail around the world in most major cities, and nearly all modern rail yards and shipping ports. Civilian and military navigation, distress, and search and rescue systems also fail, and airplanes are no longer able to accurately determine where they are flying or how close they are to one another without paper charts and compasses.[24]

23 Logsdon, D., & TechAmerica. (2013, May). *A Day Without Space: If our GPS enterprise was compromised, what impact would it have on our nation's economy?* Paper presented at Space-Based Positioning, Navigation and Timing National Advisory Board Meeting, Washington D.C.. Retrieved from https://www.gps.gov/governance/advisory/meetings/2013-05/
24 London Economics. (2017). *Economic impact to the UK of a disruption to GNSS.* Retrieved from UK Government Publications Office website: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/619545/17.3254_Economic_impact_to_UK_of_a_disruption_to_GNSS_-_Showcase_Report.pdf
25 National Coordination Office for Space-Based Positioning, Navigation, and Timing. (2021, February 22). GPS.gov: GPS overview. Retrieved from https://www.gps.gov/systems/gps
26 Leeuwen, J. V., Muscholl, A., Peleg, D., Pokorny, J., & Rumpe, B. (2010). SOFSEM 2010: Theory and practice of computer science: 36th conference on current trends in theory and practice of computer science. Špindleruv Mlýn, Czech Republic: Springer Science & Business Media.

Up to this point, the impact of a worst-case Kessler event has been limited to the global Internet, transportation, and communication. However, in nearly all developed countries or countries with a large geographic area, electric grids rely on GPS for maintaining grid synchronization, monitoring, and control. Electric companies rely on GPS enabled technology to maintain power grid efficiency, quickly locate faults or disruptions, and most importantly, to maintain sufficient energy supply across larger grids which may use different currents or span national borders (like in North America, Europe, and Africa).[27,28,29] As a result of the sustained loss of GPS satellites, power grids around the world will start to experience brownouts – intermittent reduction in the amount of electricity available for use. Within a day, it is likely that most large power grids around the world have failed, leaving billions without electricity and all the services that run on electricity: water, heating, cooling, natural gas pumps, etc., would be without power

Likewise, within a day, most mobile phone service would no longer function, and much of the Internet would be completely unreachable assuming you still had electricity.[30] Wireless Internet and mobile data would also be unavailable, and most cloud computing services and data centers would go down, as these technologies rely on accurate timing in order to function.[31] It is extremely likely that within a day, at least one in-air collision between airliners or a major airline crash has occurred.[30] There is also an extreme likelihood of passenger injury or death due to turbulence experienced in high altitude aircraft, which are unable to see or avoid inclement weather ahead. It is also highly likely that several thousand injuries or deaths have occurred as a result of the failure of regional power grids, traffic control systems, navigation systems, and maritime distress systems.[28,29] Government and military communications networks, which GPS and GLONASS were originally intended to serve,[29] have by now also been severely crippled, if not totally disabled.[24] Modern military operations would not be possible, and most modern defense systems would be severely limited. Larger or poorer nations would have difficulty communicating, and remote or isolated nations are likely to be completely cut off from the rest of the world.

It is very unlikely that this worst-case scenario event would occur, however it is not impossible. Moreover, this scenario and cascade of consequences illustrates the extent to which our modern civilization is dependent on satellites and space technology in order to function. The long-term effect of Kessler and Cour-Palais's so called 'ring of debris' encircling the Earth, particularly after a cataclysmic collision event, has the potential to cut off humanity's access to space for generations.[31,32] As previously noted, the 2,000-count debris field from the single collision of Iridium-33 and Cosmos-2251 won't have completely burned up in the Earth's atmosphere for many decades.

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27 NERC. (2016). *Preliminary Special Reliability Assessment Whitepaper: Extended loss of GPS Impact on Reliability.* Retrieved from North American Electric Reliability Corporation website: https://naspi.org/sites/default/files/2016-09/nerc_extended_loss_of_gps_impact_whitepaper.pdf

28 NASPI. (2020). *The North American SynchroPhasor Initiative (NASPI) response to the NIST Request for Information: Profile of Responsible Use of Positioning, Navigation, and Timing Services* (85 FR 31743). Retrieved from National Institute of Standards and Technology website: https://www.nist.gov/system/files/documents/2020/07/13/pnt0016.pdf

29 Yao, W., Liu, Y., Zhou, D., Pan, Z., Till, M., Zhao, J., ... Liu, Y. (2017). *Impact of GPS Signal Loss and Its Mitigation in Power System Synchronized Measurement Devices.* In 2017 IEEE Power & Energy Society General Meeting (PESGM). Chicago, IL: Institute of Electrical and Electronics Engineers (IEEE). DOI: 10.1109/PESGM.2017.8274578

30 Dvorsky, G. (2015, June 4). What would happen if all our satellites were suddenly destroyed?. Retrieved from https://io9.gizmodo.com/what-would-happen-if-all-our-satellites-were-suddenly-d-1709006681?IR=T

31 Logsdon, D., & TechAmerica. (2013, May). *A Day Without Space: If our GPS enterprise was compromised, what impact would it have on our nation's economy?* Paper presented at Space-Based Positioning, Navigation and Timing National Advisory Board Meeting, Washington D.C.. Retrieved from https://www.gps.gov/governance/advisory/meetings/2013-05/

32 Kessler, D. J., Johnson, N. L., Liou, J. C., Matney, M., & McQuerry, S. C. (2010). The Kessler Syndrome: Implications to Future Space Operations (AAS 10-016). In *33rd, Rocky Mountain Guidance and Control Conference* (p. 16). Breckenridge, CO: American Astronautical Society

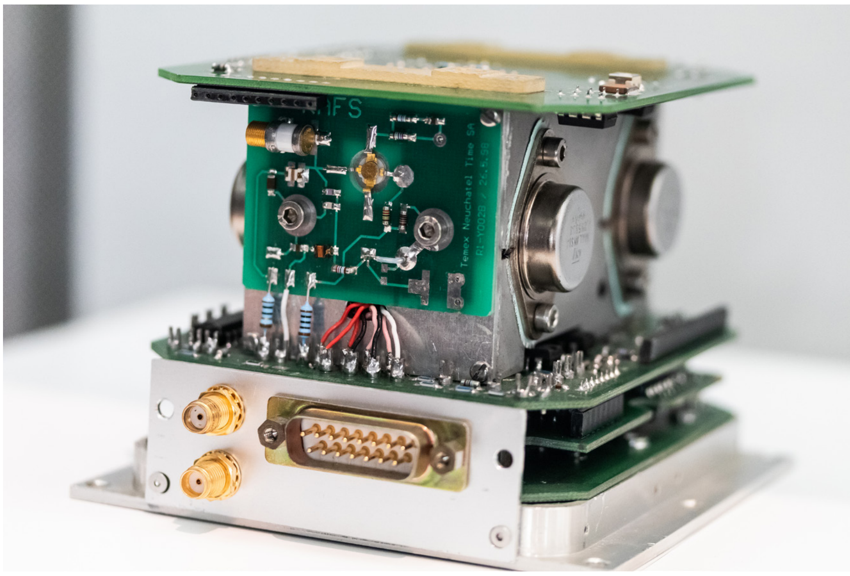


Fig. 10:

Tear-down of a miniaturized Galileo Rubidium atomic clock. Source: CV32 Photography. (n.d.). *Galileo atomic clock prototype* [Photograph]. Retrieved from https://www.flickr.com/photos/cv32photography/48855979092/

Fig. 11:

Current generation Boeing GPS IIF-6 satellite in final preparation for launch. Source: Boeing. (n.d.). *GPS IIF-6 ready for launch* [Photograph]. Retrieved from https://flic.kr/p/nyYZrh

The needs and demands of modern civilization show no signs of slowing, as more and more people are able to access the Internet, demand is ever greater for streaming services and content. With satellite technology becoming cheaper and more widely available, more and more governments and private companies are looking to launch more satellites in the coming years. So too are universities, colleges, and even high schools in some instances. In recent years, private companies have made bold public announcements regarding their immediate plans for new satellite constellations.

Amazon's *Project Kupier*, announced in 2019, aims to launch as many as 3,200 satellites into Low Earth Orbit to provide broadband Internet to customers around the world.[33,34] British and Indian-owned OneWeb, which recently emerged from bankruptcy, plans to continue launching roughly 6,700 satellites for their Internet service, in addition to the 146 satellites already in orbit.[35,36] Most famously, SpaceX's *Starlink* constellation of broadband satellites grows larger every month, with a total of 1,381 satellites in orbit, and plans for upwards of 10,000 total in the coming years.[37,38] In March 2021 alone, 240 Starlink satellites were put into Earth orbit.[33]

Even as calls to manage these enormous satellite constellations grow louder, citing the loss of clear night skies, impacts to astronomical observation, and of course space debris,[38,39] these companies and many others continue to be granted launch permits by governments. Here in New Zealand, our isolated geographic location makes us an ideal location for rocket launches,[40] something the government has been promoting since 2017 with the creation of the New Zealand Space Agency and passage of the Outer Space and High Altitude Activities Act.[41] It is therefore incumbent upon all of us to do our part to ensure that launch permits issued in New Zealand contain real and practical failsafe plans for debris and disaster mitigation which go above and beyond international standards.

Reducing the number of satellites launched into orbit requires action on part of the governments of the world's space faring nations, through policies which limit satellite launches to critical missions only, with a strict definition of criticality. Likewise, reducing the amount of space debris in orbit requires the development of technologies and methods that can be used to collect and dispose of such debris. Governments which issue launch permits for constellations of hundreds or more satellites must reevaluate the processes and criteria for their approvals. But without public awareness of the issue, it is likely that governments and corporations will continue to launch more and more satellites into space.

33 Sheetz, M. (2019, April 4). Amazon wants to launch thousands of satellites so it can offer broadband internet from space. Retrieved from https://www.cnbc.com/2019/04/04/amazon-project-kuiper-broadband-internet-small-satellite-network.html
34 Henry, C. (2019, July 8). Amazon lays out constellation service goals, deployment and deorbit plans to FCC. Retrieved from https://spacenews.com/amazon-lays-out-constellation-service-goals-deployment-and-deorbit-plans-to-fcc/
35 Foust, J. (2021, January 14). OneWeb slashes size of future satellite constellation. Retrieved from https://spacenews.com/oneweb-slashes-size-of-future-satellite-constellation/
36 Brodkin, J. (2017, October 4). SpaceX and OneWeb broadband satellites raise fears about space debris. Retrieved from https://arstechnica.com/information-technology/2017/10/spacex-and-oneweb-broadband-satellites-raise-fears-about-space-debris/
37 Clark, S. (2021, January 24). SpaceX smashes record with launch of 143 small satellites – Spaceflight now. Retrieved from https://spaceflightnow.com/2021/01/24/spacex-launches-record-setting-rideshare-mission-with-143-small-satellites/
38 Etherington, D. (2021, March 24). SpaceX launches 60 more Starlink satellites, making 240 launched this month alone. Retrieved from https://techcrunch.com/2021/03/24/spacex-launches-60-more-starlink-satellites-making-240-launched-this-month-alone
39 Berger, E. (2020, November 2). NASA objects to new mega-constellation, citing risk of "catastrophic collision". Retrieved from https://arstechnica.com/science/2020/11/nasa-objects-to-new-megaconstellation-citing-risk-of-catastrophic-collison/
40 New Zealand Space Agency. (2020, October 2). Space-related opportunities in New Zealand. Retrieved from Ministry of Business, Innovation and Employment website: https://www.mbie.govt.nz/science-and-technology/space/space-related-opportunities-in-new-zealand/
41 New Zealand Parliamentary Counsel Office. (2017). Outer Space and High-altitude Activities Act 2017. Retrieved from New Zealand Legislation website: https://www.legislation.govt.nz/act/public/2017/0029/latest/whole.html

Fig. 12:

Starlink satellite constellation passes over the Southwestern U.S. Source: McKendrick, R. (2021, February 11). *Starlink* [Photograph]. Retrieved from https://www.flickr.com/photos/mckendrickphotography/50958414037/

Fig. 13:

Starlink satellite constellation passes over Bottesford, England, on 1 May 2020. Source: Stones, A. (2020, May 1). *Starlink satellites* [Photograph]. Retrieved from https://www.flickr.com/photos/andystones64/49842285588/

Fig. 14:

Rocket Lab launch from Mahia Peninsula, New Zealand, on 6 December 2019, carrying a payload of micros-astellites to orbit. Source: Gully, B. (2020, February 28). *NASA Astronomy Picture of the Day* [Photograph]. Retrieved from https://apod.nasa.gov/apod/ap200228.html

SECTION IV: WHY I MADE THIS

Author’s background and time at Massey

For the past twelve years, I have pursued a career in graphic design, working in independent design agencies, and in small and large enterprises both private and public. While my design practice often covers a broad variety of design disciplines, most of my design work has related to visual identity development, business communication systems, and data visualizations. While some of this work has been released publicly and seen widespread use, much of it has remained safeguarded in corporate boardrooms or shrouded behind non-disclosure agreements. More recently, however, my work has increasingly involved art direction and a few high-profile design projects. In each case, and especially for projects which are complex and multifaceted, I make it a point to devote a significant amount of time to research before putting pen to paper (or cursor to screen, as the case may be).

Fig. 15:

Data visualization elements for the New Zealand Research Information System, designed as part of regular employment at the Ministry of Business, Innovation and Employment, in 2019.

Fig. 16:

Business communication system and myriad collateral for Managed Isolation and Quarantine, designed collaboratively as part of regular employment at the Ministry of Business, Innovation and Employment, in 2020.

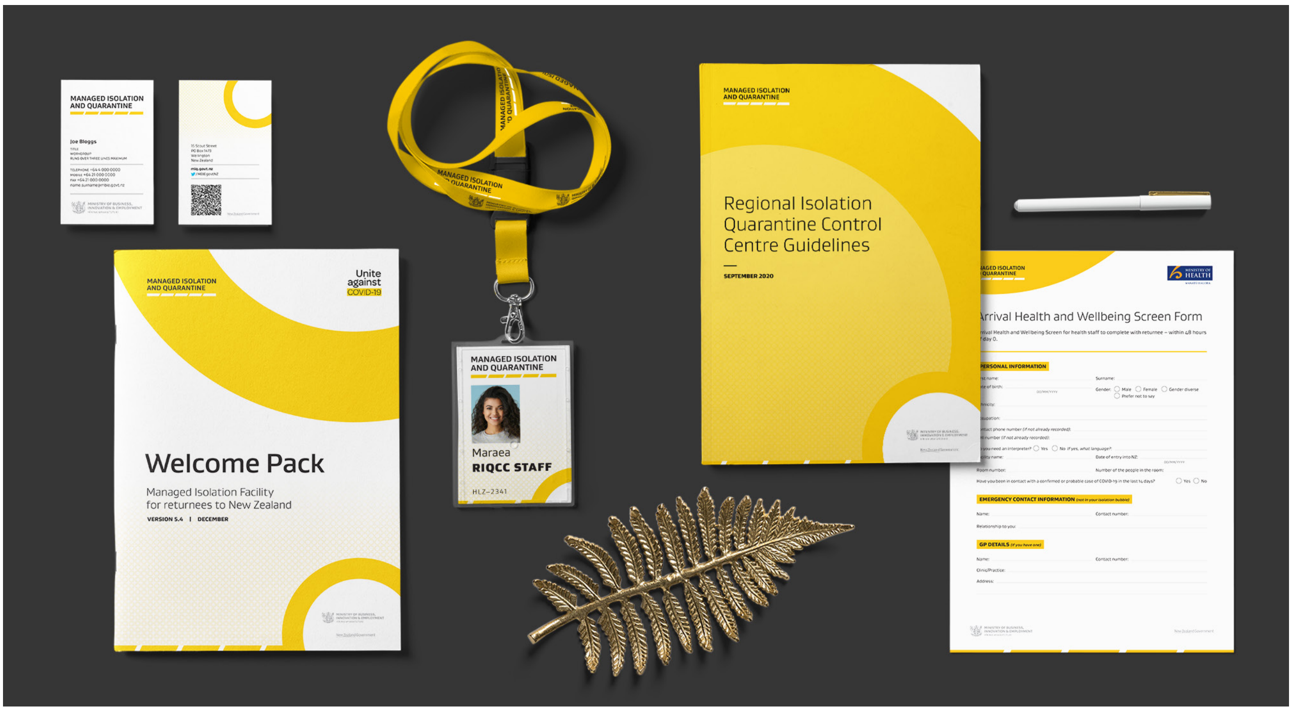


Fig. 17:

Preview of the new visual identity for the New Zealand Government, designed as part of regular employment at the Ministry of Business, Innovation and Employment, from 2019–2021.

Fig. 18:

Business communication system for Standards New Zealand, designed collaboratively as part of regular employment at the Ministry of Business, Innovation and Employment, in late 2020.

Design at its most fundamental, graphic or otherwise, can best be described as the development of objects, processes, and/or systems based on a predetermined set of requirements or specifications which, when completed, achieve specific outcomes or goals. In the study of visual communication design and the practical disciplines (i.e. graphic design, advertising, industrial design, etc.) that follow, those objects, processes, and/or systems are meant to achieve the goal of communicating a specific message, feeling, or experience which informs and influences or drives a particular action. In short, design is the process and the act of improving the visual appearance and function of messages and information.[42]

As a discipline, visual design has its roots in early art practices. The use of created objects to communicate information has existed since the dawn of humanity. From political billboards to automobiles, advertisements, gadgets, books, video games, and everything in between, design is being used to communicate messages, to make people feel, think, or do certain things, and more generally to create or influence the experience of everyday life.

During my time at Massey University, I have experimented with two design related disciplines, which were new to me: mobile app development, in the form of *Plastico*; and physical data visualization, in the form of *Plastico II*. Recent media attention directed at plastic drinking straws, their ubiquity, and subsequent public shaming, inspired my investigation into the issue which resulted in these two experimental projects.

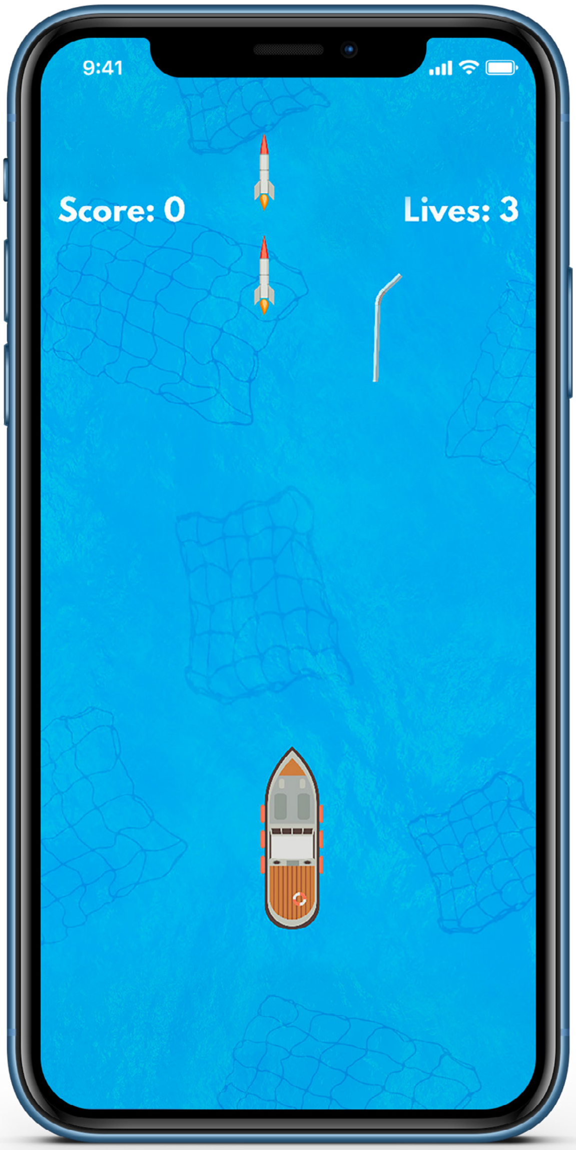
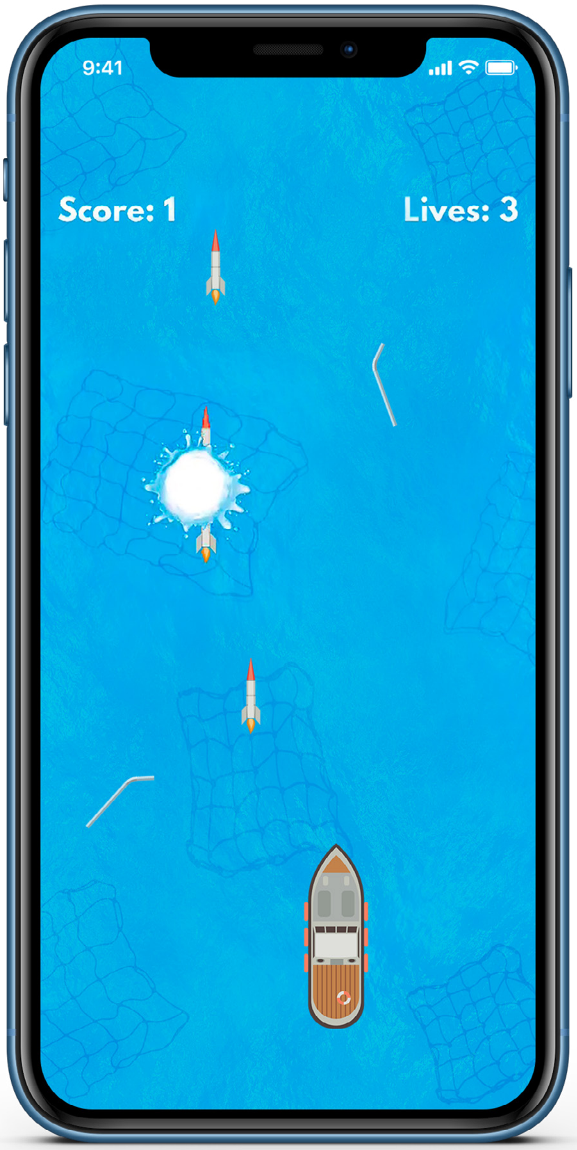


Fig. 19–20:

Screenshots from Plastico, my mobile game app for iOS where users must shoot and destroy plastic straws in the ocean, while fishing nets surround and permeate the ocean's surface.

42 AIGA. (n.d.). What is design?. Retrieved April 17, 2021, from https://www.aiga.org/what-is-design



In the *Plastico* project, I attempted to blend the simplification of complex data with interactivity under a veneer of whimsical sarcasm. *Plastico* is a mobile app developed for iOS devices where a player operates an ocean clean-up vessel at sea, firing comically oversized missiles at plastic straws as they float by, all the while ignoring large, partially submerged fishing nets. The goal of the app was to showcase the disparity in ocean plastic pollution between consumer use plastic, more specifically drinking straws, and plastic detritus from commercial fishing. It's delivery as a simplistic, silly app addresses the 'bizarreness and humorous effect,' a cognitive bias toward better remembering the absurd and the amusing.[43]

The data that informed *Plastico* was based on a 2018 study published in the journal Nature on the composition, size, and projected future movement and growth of the Great Pacific Garbage Patch. In these findings, 92% of plastic in the Great Pacific Garbage Patch could be traced back to commercial fishing, with 46% of found plastic being abandoned nets.[44]

43 Schmidt, S. R. (2012). Extraordinary Memories for Exceptional Events: Essays in Cognitive Psychology. *Europe's Journal of Psychology, 8(3).* Retrieved from https://doi.org/10.5964/ejop.v8i3.501
44 Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., ... Reisser, J. (2018). Evidence that the great Pacific garbage patch is rapidly accumulating plastic. *Scientific Reports, 8(1).* doi:10.1038/s41598-018-22939-w

Plastico II served as a follow-up to the iOS app and my first foray into object making. As the name suggests, *Plastico II* was based on the same scientific study and data as it's predecessor, and was meant to convey the same message, albeit with less whimsy and a more concise expression of the relationships between fishing and consumer plastic pollution. The work was presented as a wall mounted physical data visualization, featuring an accurate representation of plastic pollution originating from fishing activity (in the form of fishing nets), versus consumer plastics (in the form of a lone plastic straw), both of which were encased in acrylic. Surrounding these were four photographs of abandoned nets off the coast of Papua New Guinea, also encased in acrylic. The arrangement of the individual components on the wall was meant to resemble the molecular structure of polyethylene, the most common form of plastic in the world, in its most stable staggered chain conformation.[45]

Environmental damage, caused almost exclusively by human activity, is a threat that has the potential to directly impact everyone on Earth in the near future, though it is wholly preventable. Unfortunately, our innate cognitive biases prevent us from recognizing, prioritizing, or acting on the knowledge of this very real threat. A product of our survival, the human brain has evolved to prioritize immediate threats to us or our direct offspring, and to conserve effort by relying on others better positioned to address a threat, and to avoid changing behavior patterns even if they are no longer beneficial.[46]

Specifically, the cognitive biases affecting our ability to fully accept and act on issues of climate change and the environment include: 1) *Escalation of commitment*, where a group continues actions or decisions more earnestly in the face of evidence of negative outcomes of same.[46,47] 2) *Hyperbolic discounting*, where immediate benefits are preferred over long-term ones, even if long-term benefits are greater.[47] 3) *The bystander effect*, where people are less inclined to act when facing a problem as a group rather than as individuals.[46,48] 4) *Discounting the future*, where people tend to place greater concern on the outcomes in the present or near-future, rather than outcomes that impact future generations.[46,47]

Plastico attempted to create an engaging experience through interactivity, though the underlying message was ambiguous and easily lost. I decided, then, to design *Plastico II* to be explicit in its message conveyance and therefore much more effective: as demonstrated during its release on October 4th, 2019. The efficacy of *Plastico II* is owed, in part, to the efforts of the previous *Plastico* project. However, *Plastico II* was specifically designed to maximize data density and integrity, while reducing unnecessary junk or decoration, in order to display complex/abstract data in a simple and easily understood way.[49,50]
By doing this, the intention was to cut through, or otherwise bypass, those innate cognitive biases if only for a moment to get the message across. Capitalizing on the principles of good data visualization employed in *Plastico II*, and expanding on its success, became the goal for this thesis project.

45 Bennett, R. A. (2003, October 7). Thermal Physics of Polymers. Retrieved from https://www.reading.ac.uk/physicsnet/units/2/ph2001/PH2001.htm [Word Document]
46 Haselton, M. G., Nettle, D., & Murray, D. R. (2015). The evolution of cognitive bias. *The Handbook of Evolutionary Psychology*, 1-20. doi:10.1002/9781119125563.evpsych241
47 Brockner, J. (1992). The escalation of commitment to a failing course of action: Toward theoretical progress. *Academy of Management Review*, 17(1), 39-61. doi:10.5465/amr.1992.4279568
48 Hortensius, R., & de Gelder, B. (2017). From empathy to apathy: The bystander effect revisited. *Current Directions in Psychological Science*, 27(4), 249-256. doi:10.31234/osf.io/4jr5s
49 Ware, C. (2020). *Information visualization: Perception for design* (4th ed.). Burlington, MA: Morgan Kaufmann.
50 Tufte, E. R. (2001). *The visual display of quantitative information* (2nd ed.). Cheshire, CT: Graphics Press.

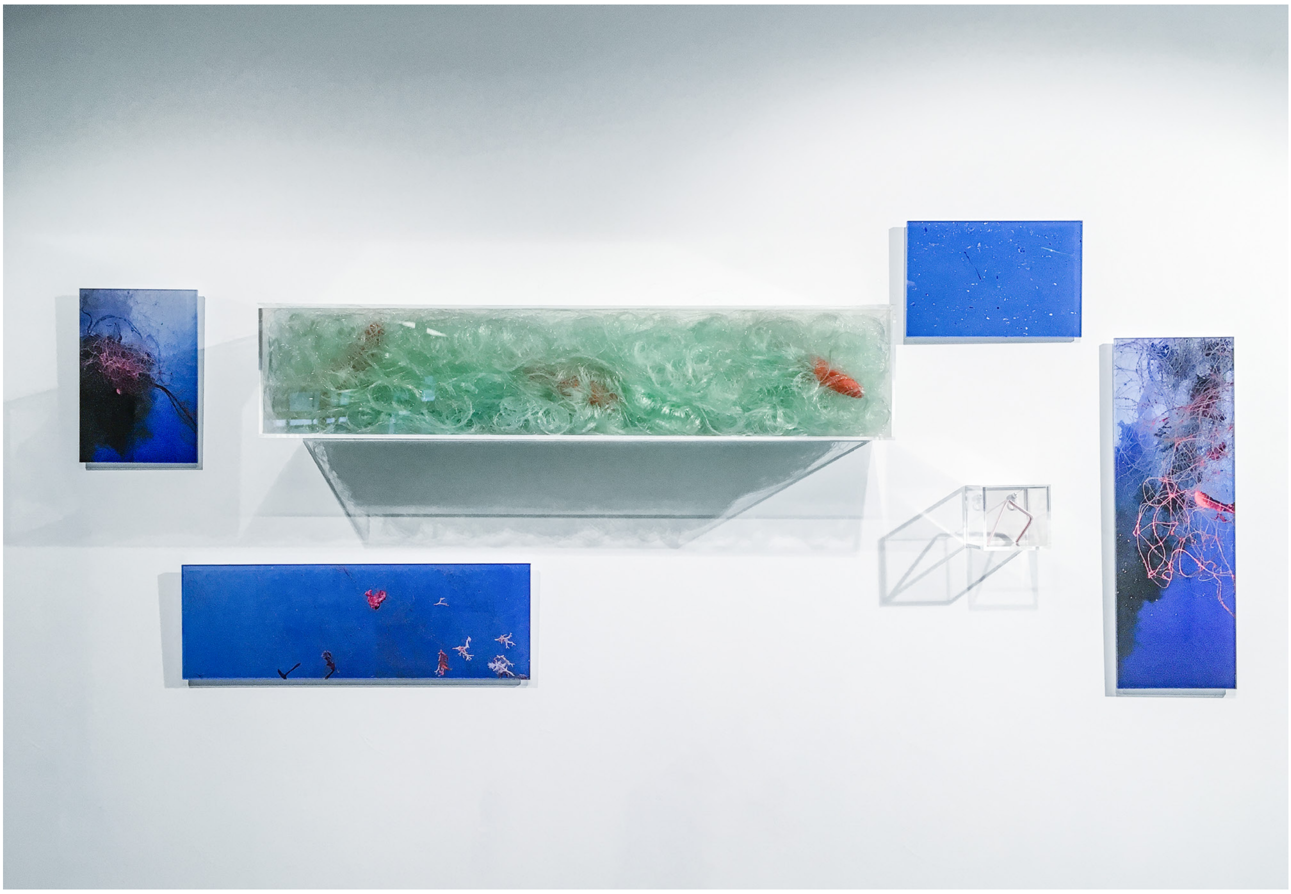


Fig. 21–22:

Plastico II installation at Massey University, on October 4th, 2019, showing the disparity in consumer versus commercial fishing pollution in the Great Pacific Garbage Patch.

Project background

In recent years, data visualizations have been increasingly relied upon to make sense of ever expanding data that is being gathered, collected, and produced by our technology saturated society. However, the practice of creating readily understood visual representations of complex or abstract data has existed for tens of thousands of years.

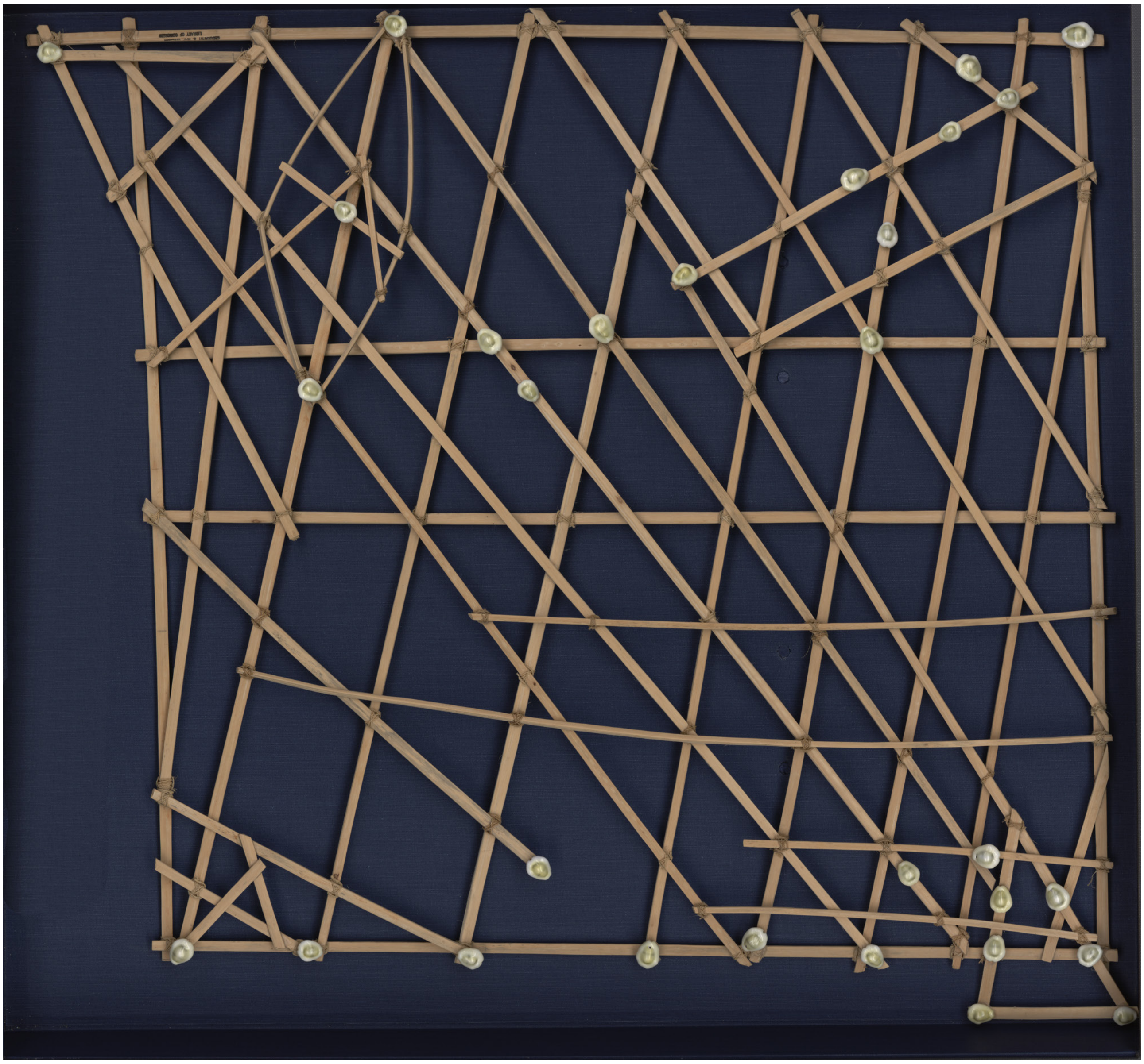
Some of the earliest uses of data visualizations pertain to the understanding and communication of large, complex systems and how humans relate to them. For instance, the famous cave paintings in Lascaux, France depict star maps of the Pleiades, Taurus, and Orion constellations circa 14,000 BC.[51] For centuries, and long before Europeans dared to lose sight of their own shores, the people of the Marshall Islands used elaborate physical maps, known as the *Marshallese Stick Charts*, which were used to model and predict ocean currents and swells for navigation in the Pacific.[51,52]

Quaint though these examples may seem to modern eyes, both effectively made profoundly complex data accessible, simplified, and readable to viewers who know how to read them. They accomplish this by presenting enough information that the viewer is able to understand the message without being overloaded with superfluous facts, figures, or related information. Both of these examples can also be understood by viewers regardless of language and with minimal context provided. In particular, the Marshallese stick chart uses simple lines and dots (seashells) to create a map, tapping in to the basic foundations of visual creation to convey a message that is just as accessible as any road map or ocean chart made today.

Fig. 23–24:

The fourth bull and the third bull, cave painting star charts from Lascaux, France. Source: Ministère de la Culture. (14,000 BC). *The Third & Fourth Bull* [Photograph]. Retrieved from https://archeologie.culture.fr/lascaux/en/mediatheque

51 Friendly, M. (2008). *Milestones in the history of thematic cartography, statistical graphics, and data visualization.* Retrieved from https://math.usu.edu/~symanzik/teaching/2009_stat6560/Downloads/Friendly_milestone.pdf
52 Genz, J. H. (2016). *Resolving Ambivalence in Marshallese Navigation: Relearning, Reinterpreting, and Reviving the "Stick Chart" Wave Models.* Structure and Dynamics, 9(1). Retrieved from https://escholarship.org/uc/item/43h1d0d7



<u>Fig. 25:</u>

Marshallese navigation chart indicating sailing directions for atolls and islands in both the Eastern and Western chains of the Marshall Islands. Source: Library of Congress. (1920). *Marshall Islands stick chart, Rebbelib type* [Wood and Shell Model]. Retrieved from https://lccn.loc.gov/2010586182

Modern data visualizations operate in much the same way as their ancient predecessors: simplifying complex, vast data in order to make it easily understood, and informing decisions based on the collected evidence and prior experience of others. Living in an era of post-globalization, where events in one part of the world have observable run-on effects and impacts in other parts of the world, it is increasingly important for people to be able to understand complex global issues in order to make informed decisions. As our knowledge and understanding of the world, and our ability to predict and forecast, has expanded, so too has our awareness of ever larger and more complex problems. Data visualization must not only communicate complex problems in an easily understood and memorable way, but it must also maintain scientific accuracy and not be done in a way that is misleading to the casual observer.[53]

The best data visualizations are memorable and recognizable, as well as factually correct.[53] The use of color, visually complex elements, and recognizable objects increases the memorability of a visualization.[54] Incorporating, but limiting, the proliferation of these elements to a relatively small amount, in a given visualization, allows observers to spend more time exploring and observing the visualization as a whole.[53,54] Likewise, avoiding the use of decorative or superfluous elements, known as "chartjunk," further helps enhance the recognition and memorability of data vizualizations.[53] These characteristics are shared by all enduring, memorable visualizations, be they simple navigational charts or advanced atmospheric data modeling, and are what underpin the efficacy of *Plastico II* and, hopefully, *Satellites*.

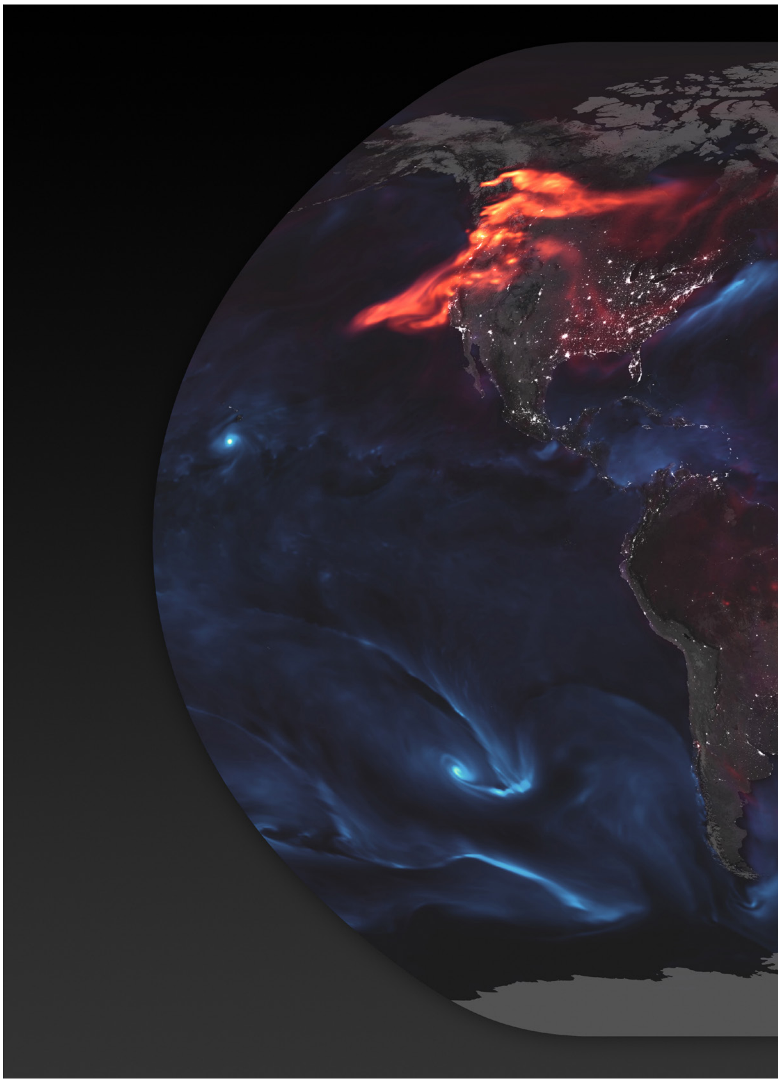


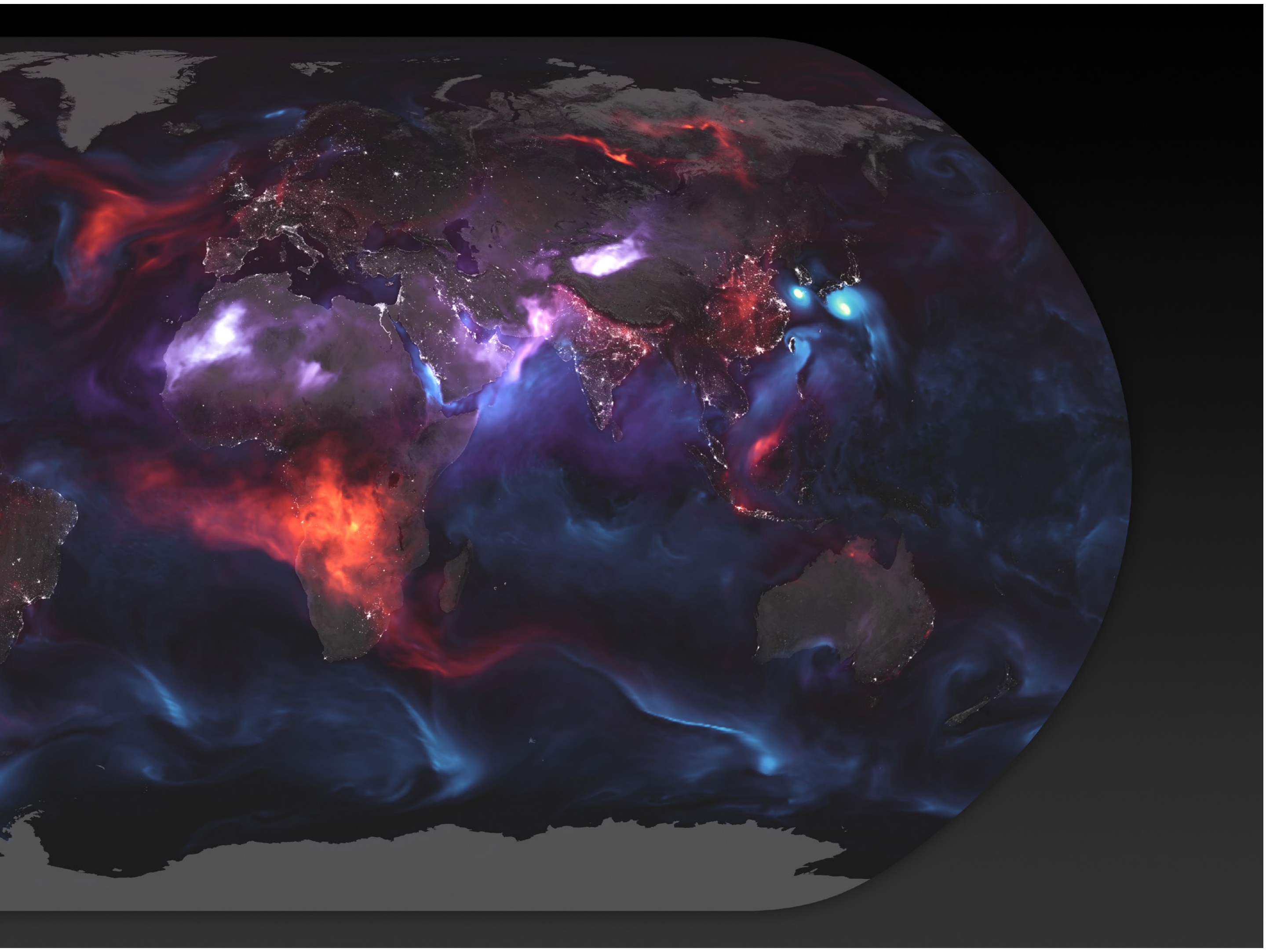
Fig. 26:

The Goddard Earth Observing System Forward Processing model's output for aerosols on August 23, 2018. Red indicates black carbon emitted from fires and industry, blue indicates sea salt aerosol, and purple indicates dust. A layer of night light data from the Visible Infrared Imaging Radiometer Suite in Suomi, Finland is overlaid. This data visualization is highly effective because it makes careful use of recognizable objects (the map), succinct use of colour, and no superfluous decoration. Source: NASA. (2018). *Just Another Day on Aerosol Earth* [Satellite Image Composite]. Retrieved from https://earthobservatory.nasa.gov/images/92654/just-another-day-on-aerosol-earth

Fig. 27:

A physical data vizualization showing the quantity and trajectory of bullets which struck their intended targets during the historical assassinations of Malcolm X, King Faisal, and Amadou Diallo. Source: Clar, J. (2010). *A Moment Defined By A Point And A Line* [Data Sculpture]. Retrieved from https://www.jamesclar.com/portfolio_page/a-moment-defined-by-a-point-and-a-line-2010/

53 Tufte, E. R. (2001). *The visual display of quantitative information* (2nd ed.). Cheshire, CT: Graphics Press.
54 Borkin, M. A. (2013). *Perception, Cognition, and Effectiveness of Visualizations with Applications in Science and Engineering* (Doctoral dissertation). Retrieved from http://nrs.harvard.edu/urn-3:HUL.InstRepos:12274335



Process and design decisions

The primary question my thesis addresses is: how data visualizations can be used to effectively communicate the scope and scale of human activity's impact on the environment. Specifically, our wanton disregard for outer space and the rapidly increasing amount of satellites and debris that we keep launching into orbit. Where the *Plastico* projects focused on the pollutant man-made materials (plastic), their sources (fishing and consumers), and relationships between the two in their sub-environment (the ocean), *Satellites* addresses man-made objects in low Earth orbit, their ubiquity in the night sky, and their impact on future human activity. Addressing possible solutions to environmental problems, however, falls outside the scope of this work, which instead focuses on addressing comprehension of such problems. Keeping the focus of the work to man-made satellites in orbit, the debris fields of the first satellite collision and intentional destruction, and the debris of dead rocket bodies, prevents the overload of information in any given poster in the *Satellites* series. Likewise, limiting colors, text labels, and explanatory information, to an absolute minimum will help increase the level of engagement and understanding[55] of what the project is trying to convey: that we have simply put too much junk in space.

My first idea for *Satellites* was to create a second physical data visualization using cubes of various materials to illustrate the volume of space junk in orbit. This, however, quickly proved to be too expensive an endeavor, and after careful thought, perhaps not so effective. The decision to return to my graphic design roots for this project was done for practical reasons. Rather than learn programming, which I do not enjoy, or source sculptural materials, I could focus on conveying the message of *Satellites* in the most effective way I know how.

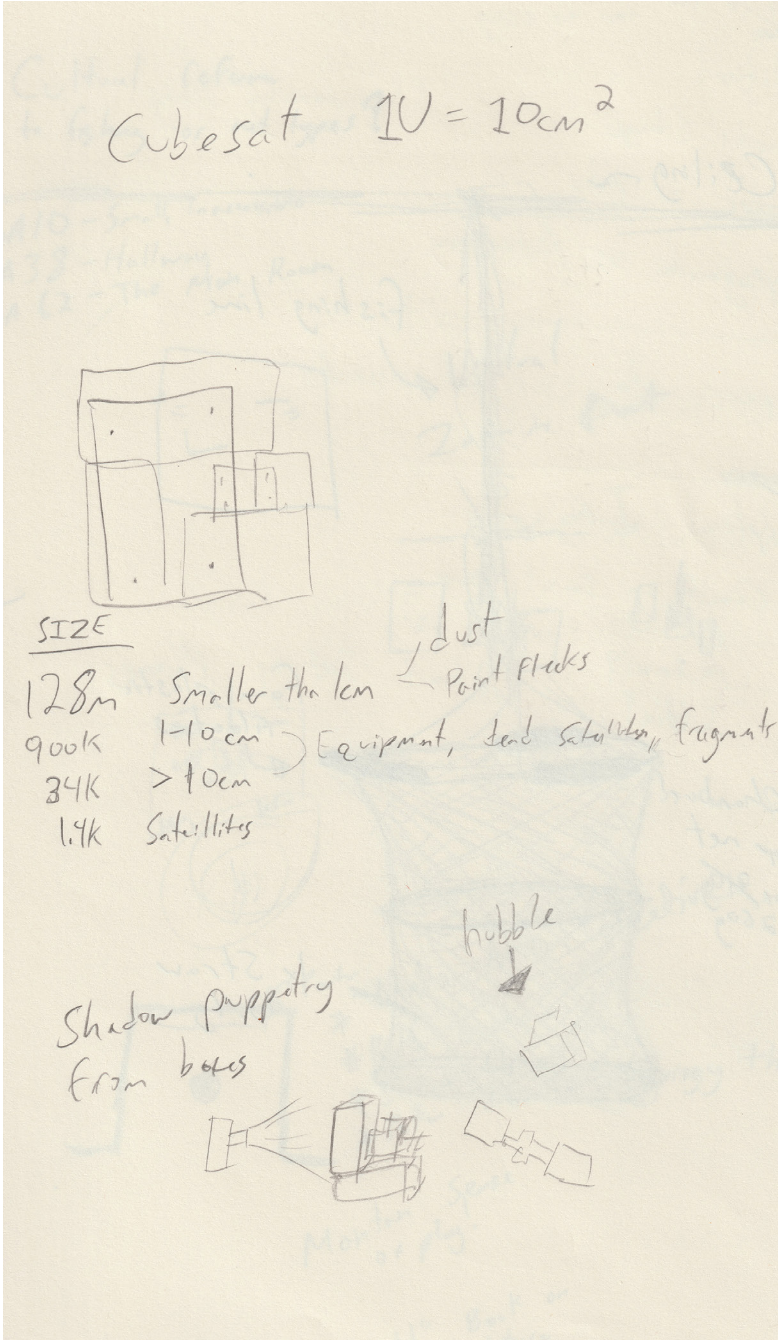
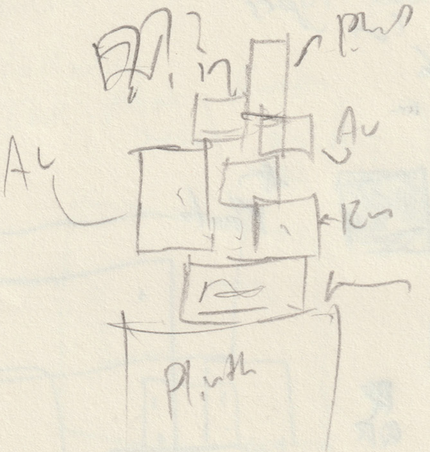


Fig. 28–29:

Scans of my Massey notebook, from about November 2019, showing the early concept for a physical data visualization of space junk, which later became *Satellites*.

55 Borkin, M. A. (2013). *Perception, Cognition, and Effectiveness of Visualizations with Applications in Science and Engineering* (Doctoral dissertation). Retrieved from http://nrs.harvard.edu/urn-3:HUL.InstRepos:12274335



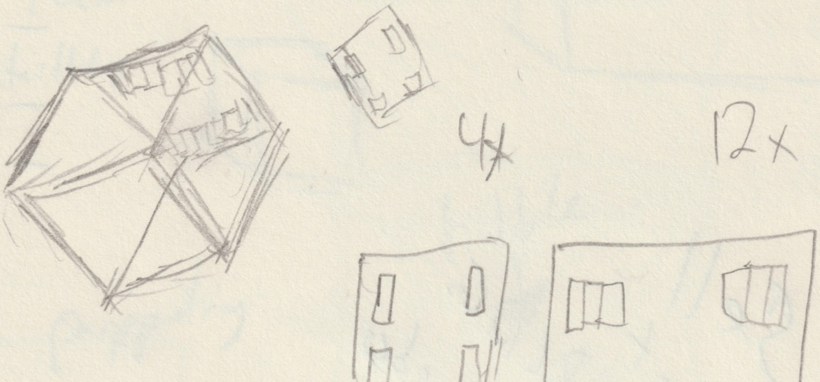
Cube Sats

Space Junk

Cube Sat Size?

Affix to Wall?

Pre-drilled holes for screws or anchors?



As luck would have it, work on this thesis was set to begin in earnest roughly two weeks before New Zealand went into lockdown in March 2020, in response to the worsening COVID-19 pandemic. Due to this, some of the early work on *Satellites* radically shifted to accommodate a new isolated and remote lifestyle. Armed with a seemingly endless stretch of free time, interrupted only by sporadic bursts of critical work for my day job at the Ministry of Business, Innovation and Employment, I set about building something which could be presented to the MFA cohort entirely virtually – with or without me present. Unfortunately, this meant deviating from my plan to create something in print, and instead go back to something digital.

The result was a website which focused on the myriad consequences of a Kessler event in Earth orbit, making use of fun and whimsical illustrations to both gloss-over and make accessible the dense and morbid fate of life on Earth during the first few days of disaster. While this long-scrolling website, called *Earthly Impacts*, existed in a medium I had no interest in working in –nor one that was particularly effective in a Zoom meeting– it did provide some good insight into how much information a new observer could take in at once and the interest/engagement that people had with the subject matter. Ultimately, the outcome of *Earthly Impacts* reaffirmed the decision to focus *Satellites* on the current state of the problem in Earth orbit, with the run-on effects available as supplementary information for the truly interested. And so, without becoming too much too quickly, my thesis project would remain firmly rooted in quantitative data visualization, rather than an amalgamation of qualitative and quantitative data. As lockdown ended, most of the country reemerged from our homes, and life began gradually returning to normal, I decided to once again try to create *Satellites* as I had intended at the start of 2020: a series of large scale printed posters.

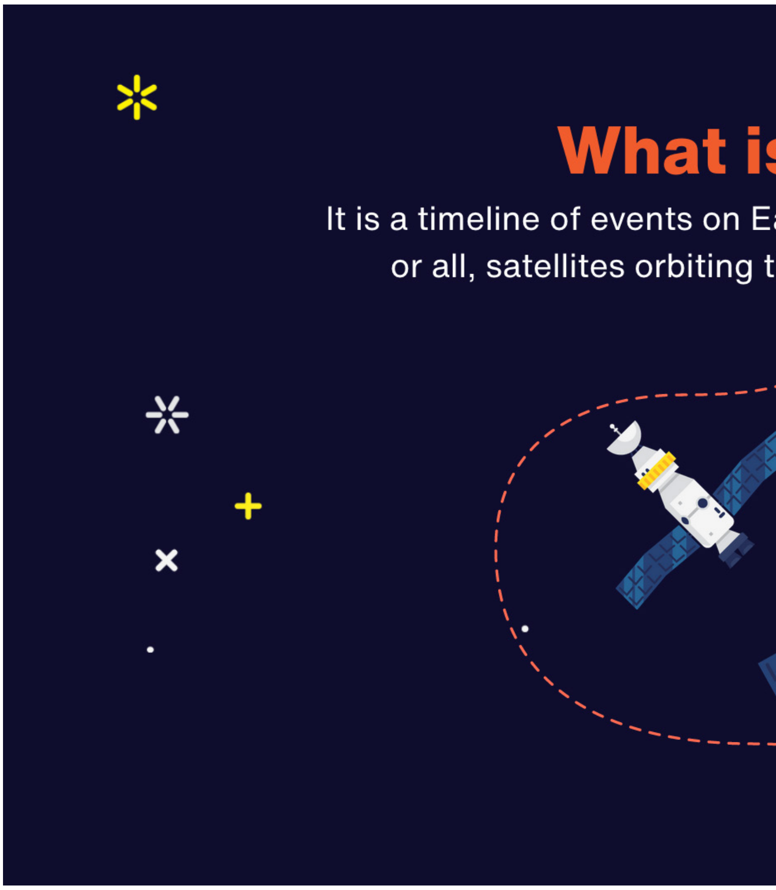


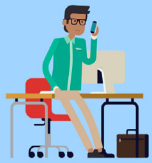
Fig. 30–37:

Earthly Impacts long-scroll website created during New Zealand's 2020 COVID-19 lockdown, highlighting the impacts of a runaway Kessler event on daily life on Earth. Content and illustrations include satellite collisions, a KiwiBank inspired ATM, the parliament building (aka: the Beehive), Air New Zealand and EasyJet inspired planes, and an airport scene inspired by the architecture of the Wellington International Airport. Source: http://earthlyimpacts.wmanning.co.nz

s This?

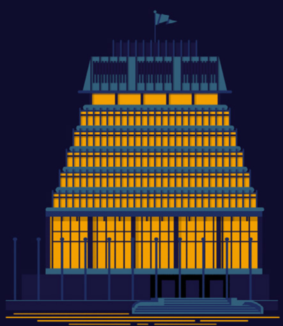
arth that would occur if most
he Earth were destroyed.

15 MINUTES



International phone calls lose audio fidelity. International internet speeds begin to drop as communications are rerouted.

The global financial system, stock markets, internet banking, and ATMs all fail.



Government communication networks are either severely crippled or totally disabled, resulting in the isolation of most governments around the world, particularly in larger or poorer nations. Remote nations are completely cut off from the rest of the world.

6 HOURS

The cascading failure of nearly every computer system on Earth would take decades to fully recover from.

12 HOURS

Most air traffic has been grounded.

The first *Satellites* poster prototype was shown in late August, 2020, at Massey University. This poster focused on the Iridum-33 and Cosmos-2251 collision debris, and was accompanied by a brief description of what the viewer was seeing. Apart from giving the viewer the impression that there was a lot of debris, the poster did not provide any further detail. There was no indication of source of debris, altitude, speed, or context. These omissions in the initial test of the project informed the specific use of color, and content in each of the posters in the final version of the Satellites poster series.

The data used to make the prototype and final version of the *Satellites* posters comes from Space-Track.org, a website operated by the United States Combined Force Space Component Command, part of the U.S. Space Force, and the 18th Space Control Squadron of the U.S. Air Force. Satellite orbital data is provided in the form of TLE (Two Line Element) data, which provides all of the attributes of a given object in orbit at any given time. This data was made public in order to reduce the risk of satellite collisions by allowing anyone to calculate possible collisions and move their satellites out of the way. The TLE data from the Space-Track.org's database, known as *SATCAT*, was imported into ArcGIS to create the initial map, before being exported to Adobe Illustrator for fine tuning. This process allowed for more creative control over the background map of New Zealand featured in the posters, as well as line thickness and color, while maintaining a high level of accuracy with the original TLE data set.

In order to keep the project focused, only data pertaining to objects in Low Earth Orbit was used in the *Satellites* project. This not only helped keep the scope of the project more manageable, but also reduced the amount of 'chartjunk' present in each poster. Since Low Earth Orbit (LEO) is the least expensive and most commonly used orbit for most man made satellites, and by extension the orbit with the greatest likelihood of experiencing a Kessler event, it seemed appropriate to keep the focus on LEO exclusively. This decision kept overcrowding on the posters to a minimum, and allowed for the linear patterns of multiple orbital pathways to shine through.

The materiality of the *Satellites* poster series is specifically designed to evoke feelings of outer space based on shared past experiences, be they educational or science fiction sources.[56] Every person on Earth knows what outer space is like, thanks to the starry night sky which appears overhead. *Satellites* taps into this common knowledge of what outer space is like by way of dark colors, low lights, and an ambient soundscape. The introduction of lighting control and ambient background music into the *Satellites* project installation, in particular, serves to enhance memory retention and object recognition by enhancing immersion into the subject matter. Multisensory experiences, no matter how elaborate, are shown to improve visual and auditory recognition.[55,56,57] This is especially true where the same or similar specific multisensory cues are employed to trigger specific memory associations.[56]

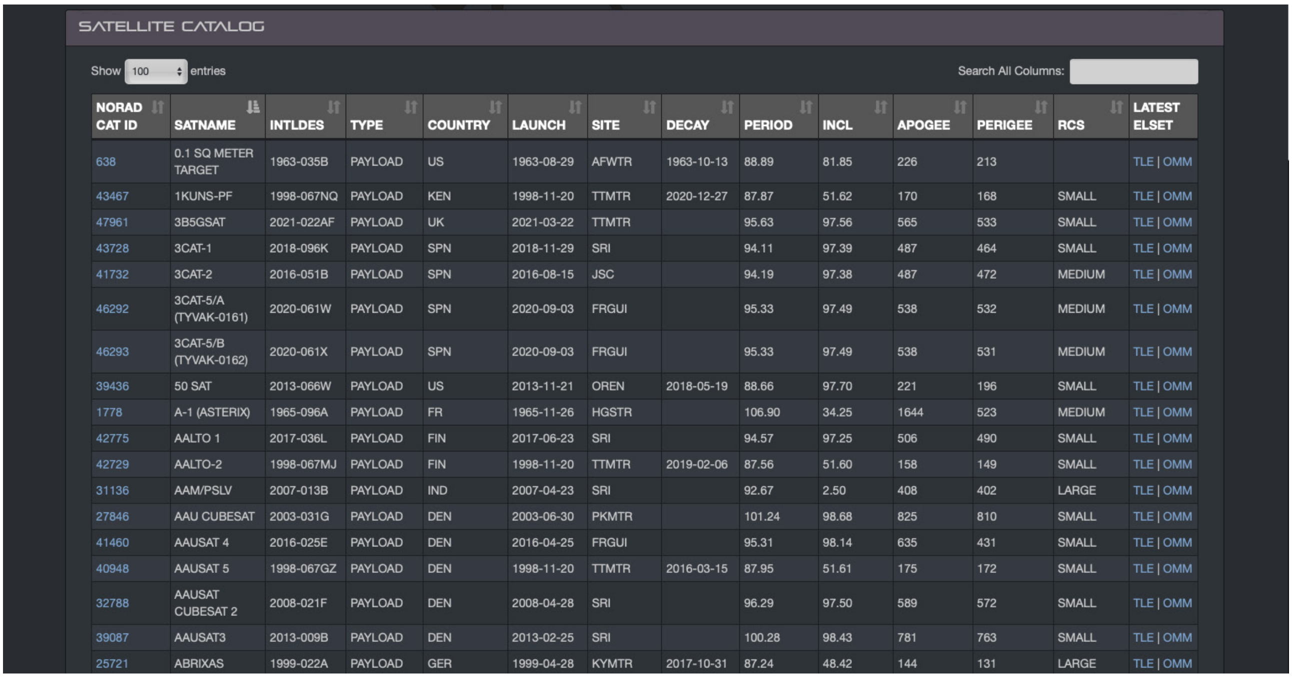
It is because of this triggered association that the poster series makes use of: 1) dark colors throughout the installation, to give the impression that one is looking into space, 2) contrasting light colors in the posters themselves, drawing from a palette of colors which are observable in the night sky, 3) dimmed lights reminiscent of twilight star observations or planetariums, and 5) ambient music with an emphasis on musical tone and atmosphere, akin to the background music of so many space operas and science fiction movies and TV shows. Likewise, this very document is designed following the 1976 NASA graphics standards manual.[58] When combined, these design choices work together to greatly enhance the memorability and recognition of the content and messaging in the *Satellites* project.

It is the goal, then, of the *Satellites* project to raise awareness of the problem of the overcrowding of Earth orbit by satellites, and that awareness of the issue persist in the observer's memory at worst, or spur them on to further investigation and possible action on this issue at best. Likewise, these posters will hopefully stand as a form of artifact, a kind of recognition to our future selves, or even future generations, which have to live with the consequences of our thirst for more satellites in space, and more, cheaper, faster throwaway technology in general. With so much garbage in the sea, garbage on the land, and garbage in the sky, the cost of our collective ignorance will be much too high.

56 Thelen, A., Talsma, D., & Murray, M. M. (2015). Single-trial multisensory memories affect later auditory and visual object discrimination. *Cognition*, 138, 148-160. doi:10.1016/j.cognition.2015.02.003
57 Matusz, P., Wallace, M. T., & Murray, M. M. (2017). A multisensory perspective on object memory. *Neuropsychologia*, 105, 243-252. Retrieved from https://doi.org/10.1016/j.neuropsychologia.2017.04.008
58 NASA. (1976). *Graphics Standards Manual* (NHB 1430.2). Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/nasa_graphics_manual_nhb_1430-2_jan_1976.pdf

Fig. 38:

Satellites test installation at Massey University, on August 10th, 2020, with single prototype poster.



SATELLITE CATALOG

Show 100 entries

Search All Columns:

NORAD CAT ID	SATNAME	INTLDES	TYPE	COUNTRY	LAUNCH	SITE	DECAY	PERIOD	INCL	APOGEE	PERIGEE	RCS	LATEST ELSET
638	0.1 SQ METER TARGET	1963-035B	PAYLOAD	US	1963-08-29	AFWTR	1963-10-13	88.89	81.85	226	213		TLE | OMM
43467	1KUNS-PF	1998-067NQ	PAYLOAD	KEN	1998-11-20	TTMTR	2020-12-27	87.87	51.62	170	168	SMALL	TLE | OMM
47961	3B5GSAT	2021-022AF	PAYLOAD	UK	2021-03-22	TTMTR		95.63	97.56	565	533	SMALL	TLE | OMM
43728	3CAT-1	2018-096K	PAYLOAD	SPN	2018-11-29	SRI		94.11	97.39	487	464	SMALL	TLE | OMM
41732	3CAT-2	2016-051B	PAYLOAD	SPN	2016-08-15	JSC		94.19	97.38	487	472	MEDIUM	TLE | OMM
46292	3CAT-5/A (TYVAK-0161)	2020-061W	PAYLOAD	SPN	2020-09-03	FRGUI		95.33	97.49	538	532	MEDIUM	TLE | OMM
46293	3CAT-5/B (TYVAK-0162)	2020-061X	PAYLOAD	SPN	2020-09-03	FRGUI		95.33	97.49	538	531	MEDIUM	TLE | OMM
39436	50 SAT	2013-066W	PAYLOAD	US	2013-11-21	OREN	2018-05-19	88.66	97.70	221	196	SMALL	TLE | OMM
1778	A-1 (ASTERIX)	1965-096A	PAYLOAD	FR	1965-11-26	HGSTR		106.90	34.25	1644	523	MEDIUM	TLE | OMM
42775	AALTO 1	2017-036L	PAYLOAD	FIN	2017-06-23	SRI		94.57	97.25	506	490	SMALL	TLE | OMM
42729	AALTO-2	1998-067MJ	PAYLOAD	FIN	1998-11-20	TTMTR	2019-02-06	87.56	51.60	158	149	SMALL	TLE | OMM
31136	AAM/PSLV	2007-013B	PAYLOAD	IND	2007-04-23	SRI		92.67	2.50	408	402	LARGE	TLE | OMM
27846	AAU CUBESAT	2003-031G	PAYLOAD	DEN	2003-06-30	PKMTR		101.24	98.68	825	810	SMALL	TLE | OMM
41460	AAUSAT 4	2016-025E	PAYLOAD	DEN	2016-04-25	FRGUI		95.31	98.14	635	431	SMALL	TLE | OMM
40948	AAUSAT 5	1998-067GZ	PAYLOAD	DEN	1998-11-20	TTMTR	2016-03-15	87.95	51.61	175	172	SMALL	TLE | OMM
32788	AAUSAT CUBESAT 2	2008-021F	PAYLOAD	DEN	2008-04-28	SRI		96.29	97.50	589	572	SMALL	TLE | OMM
39087	AAUSAT3	2013-009B	PAYLOAD	DEN	2013-02-25	SRI		100.28	98.43	781	763	SMALL	TLE | OMM
25721	ABRIXAS	1999-022A	PAYLOAD	GER	1999-04-28	KYMTR	2017-10-31	87.24	48.42	144	131	LARGE	TLE | OMM

Fig. 39:

Screenshot of SATCAT public database showing all tracked satellites and debris objects in Earth orbit. These data were used to create the Satelites posters. Source: https://www.space-track.org

Sources of inspiration

A variety of existing work has helped inform and inspire *Satellites* in varying degrees throughout the project. These notable examples have had a significant influence on the project's aesthetic direction since the very beginning. The Voyager Golden Record, of which there are copies on the Voyager I and II spacecraft, is a phonograph record containing video recordings of life on Earth.[59] The record is electroplated with gold and copper, which happen to be metals commonly used in space objects like satellites, space blankets, etc. The cover features an infographic, which was designed to be interpreted by an alien species.[59] The diagrams explain the cosmic origin of the Voyager spacecraft, as well as how to play the record correctly. Each was designed to be so simple that any being with basic science knowledge could decode the instructions and use the record. These linear forms, and the metals used in the record, influenced early versions of *Satellites*, which also rely on simple line diagrams to be read. Earlier versions of *Satellites* likewise were meant to incorporate metals or metallic colorings (though this was omitted from the final project due to costs).

One early example, which came to mind as I planned what this project might look like, comes from actual spacecraft – the most notable of which are the space shuttles which NASA operated until a few years ago. Their black and white coloration, a product of necessity for thermal performance of the vehicle, have become and iconic and enduring icon of modern space travel. Naturally, strong black and white contrast had to feature in *Satellites*.

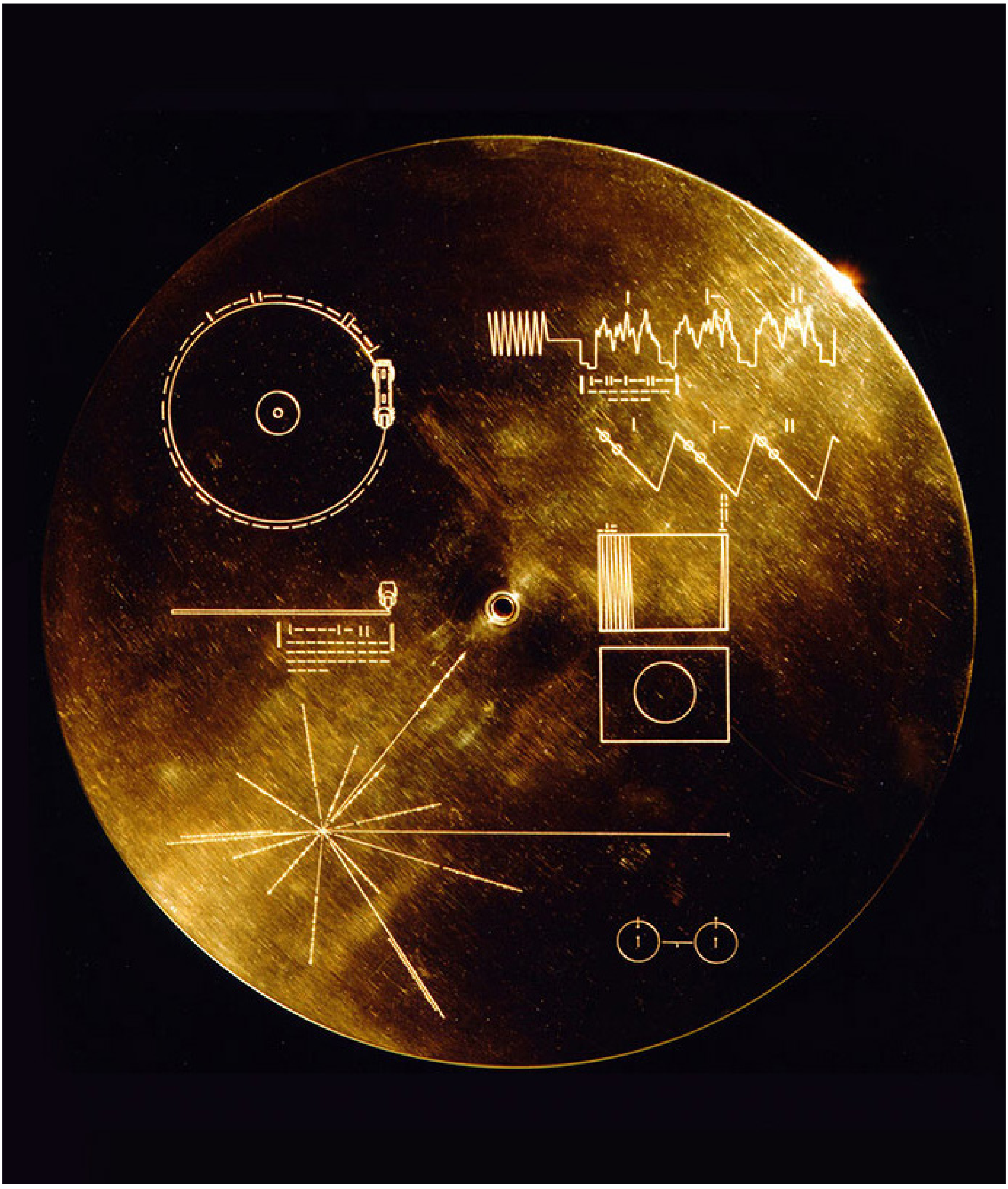
Fig. 41:

The space shuttle Endeavour on display at the California Science Center. Source: NASA/Bill Ingalls. (2012). *Endeavour Grand Opening Ceremony* (201210300009HQ) [Photograph]. Retrieved from https://www.flickr.com/photos/nasahqphoto/8139569523/

Fig. 42:

The Voyager Golden Record. Source: NASA/JPL. (1977). *The Golden Record Cover* [Photograph]. Retrieved from https://voyager.jpl.nasa.gov/golden-record/golden-record-cover/

59 NASA/JPL. (n.d.). Voyager - The Golden Record. Retrieved from https://voyager.jpl.nasa.gov/golden-record/



The installation work of Japanese artist, Ryoji Ikeda, has played a strong role in guiding the overall presentation of *Satellites* in addition to influencing the aesthetics of the posters themselves. Ikeda's work often deals with applied mathematics or mathematical concepts expressed as data or algorithmic visualizations. In his *Macro|Micro* project, created during his residency at CERN, Ikeda created large scale video projections depicting the Planck Constant as it relates to both our world (micro) and the greater cosmos (macro).[60] The *Macro* projection in particular, which made use of astronomical observations, appeared in only three colors: black, white, and a thin red line representing the Planck Constant through time.

Ikeda's *data.scape [DNA]*, an audiovisual installation, makes use of genomic sequencing to not only create a stunningly intricate data visualization, but to also generate an ambient soundscape which plays alongside it. This presentation method, and the incorporation of ambient sound, has played a strong and obvious role in how I have chosen to display *Satellites*.

In the realm of audiovisual and interactive works, I would be remiss to not have taken a close look at Patricio Gonzalez Vivo's *LineOfSight* project, which was an interactive map in which users could select a given city and see which active satellites were currently passing overhead. The map gave the precise location, speed, and other information about satellites which cross over major cities. Of course, orbital pathways and minimal color schemes abound in *LineOfSight*, offering some clues as to how this information might be approached.

60 Clement, T. (2018, July 12). *Ryoji Ikeda: Micro | macro — Art guide Australia*. Retrieved from https://artguide.com.au/ryoji-ikeda-micro-macro/

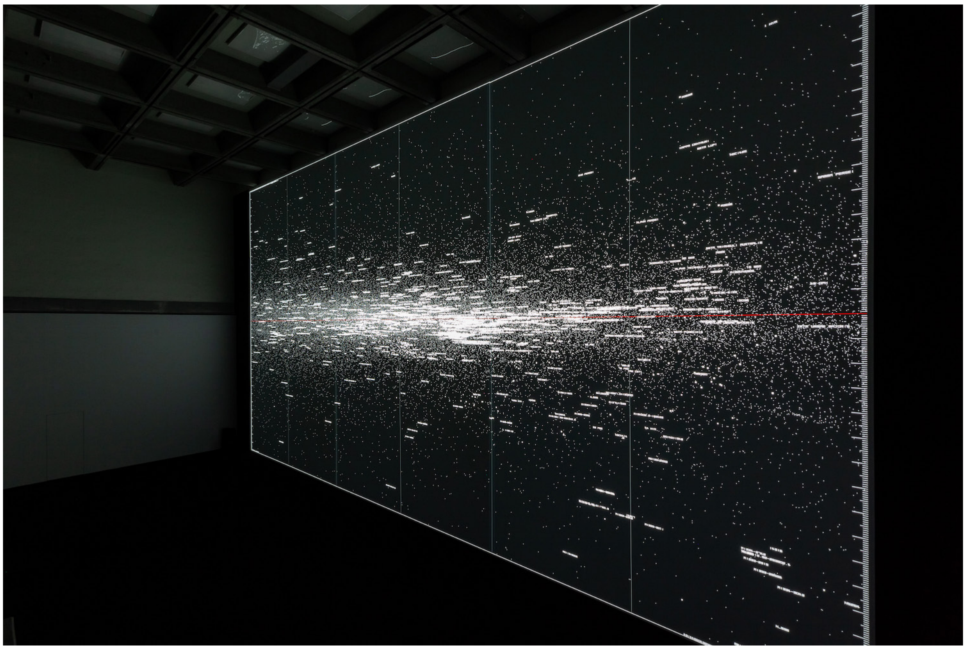


Fig. 43:

Still image of *The Planck Universe [Macro]*, a data visualization of astronomical observations set against a red line representing the Planck constant. This work helped inform the aesthetic and data visualization techniques employed in *Satellites*. Source: Ikeda, R. (2018). *The Planck Universe [Macro]* [Audio/Visual Installation]. Retrieved from https://www.ryojiikeda.com/project/x_verse/

Fig. 44:

Still image of *data.scape [DNA]*, an audio/visual installation showing a re-imagined way of displaying genetic material. This work helped inform the aesthetic and practical display/installation of *Satellites*. Source: Ikeda, R. (2019). *data.scape [DNA]* [Audio/Visual Installation]. Retrieved from https://www.ryojiikeda.com/project/datamatics/

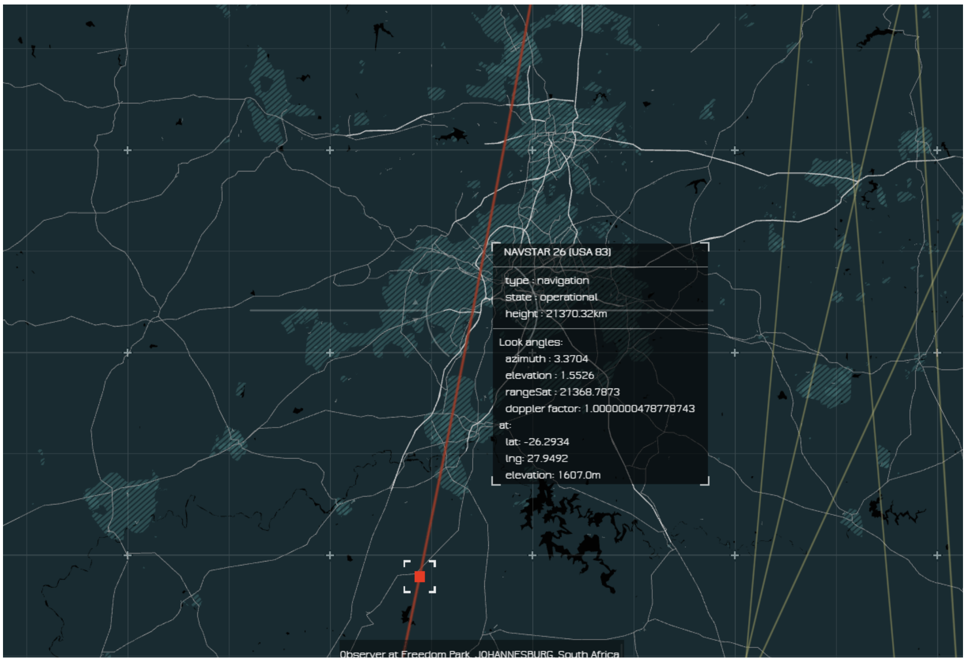
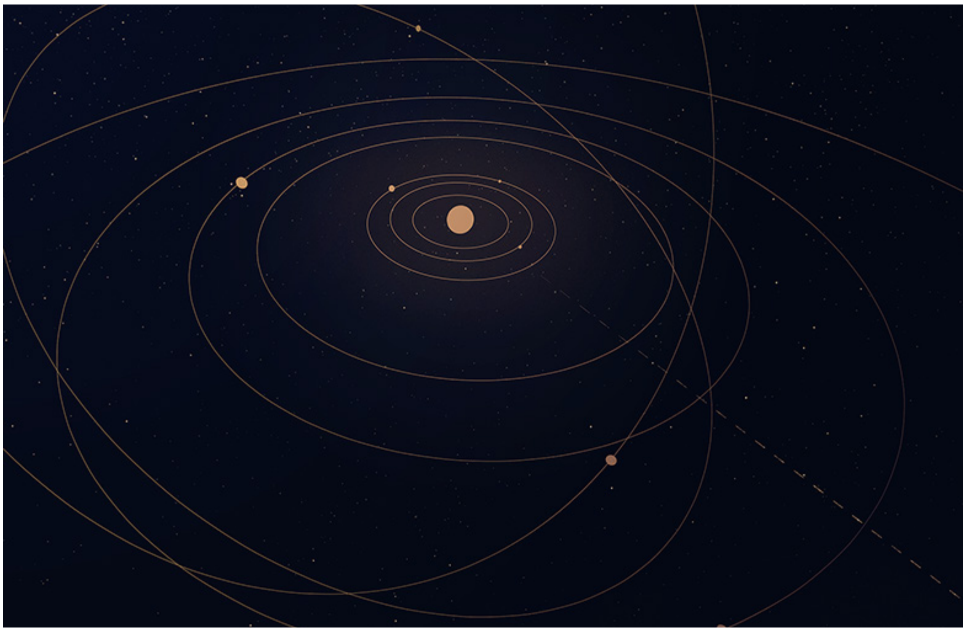


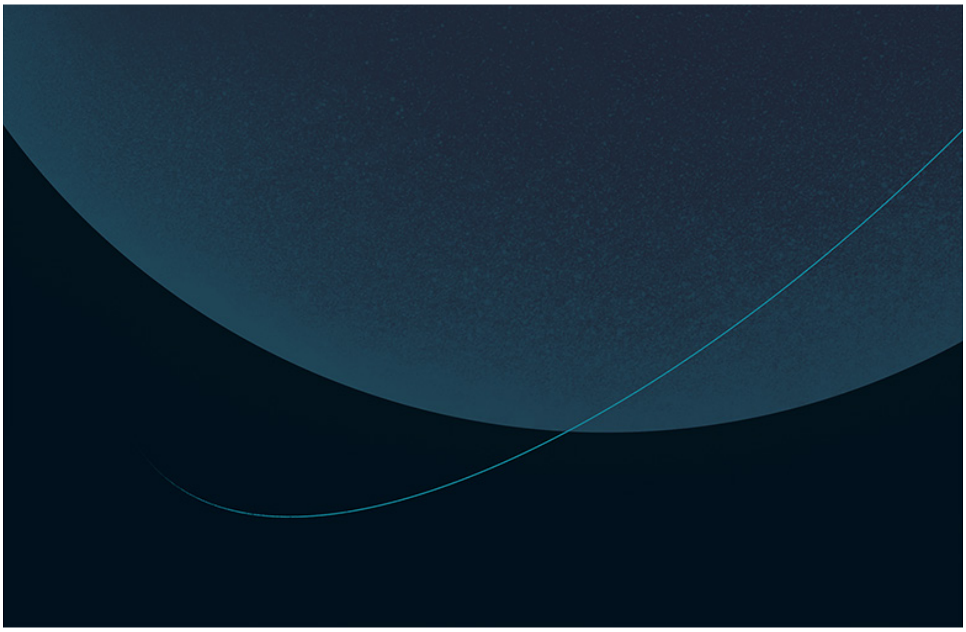
Fig. 45:

Still image of *LineOfSight*, a now-defunct open source mapping tool which shows active satellites over a given city or region. At the time of this artwork's publication, only ~2,500 active satellites orbited the Earth. This work helped inform the aesthetic and data visualization techniques employed in *Satellites*. Source: Vivo, P. G. (2015). *LineOfSight* [Screenshot]. Retrieved from http://patriciogonzalezvivo.com

Fig. 46:

Still image from *Chaos and Structure*, a series of peudo-data visualizations created as an inspirational homage to scientific discovery and the recurring patterns found in nature, from the atom to the stars. While not based on any actual data, and with no message or information to convey, this work nonetheless helped inform the aesthetic used in *Satellites*. Granular detail covering linear forms and colors work together beautifully to create a visual which exudes scientific, technological, and perhaps even cosmic knowledge. Though there are hundreds if not thousands of very thin lines used here, the work is not visually overloaded and if it were a true data visualization, it would no doubt be a highly effective one. Source: Plakhova, T. (2011). *Chaos and Structure* [Print]. Retrieved from http://www.complexitygraphics.com/CHAOS-AND-STRUCTURE





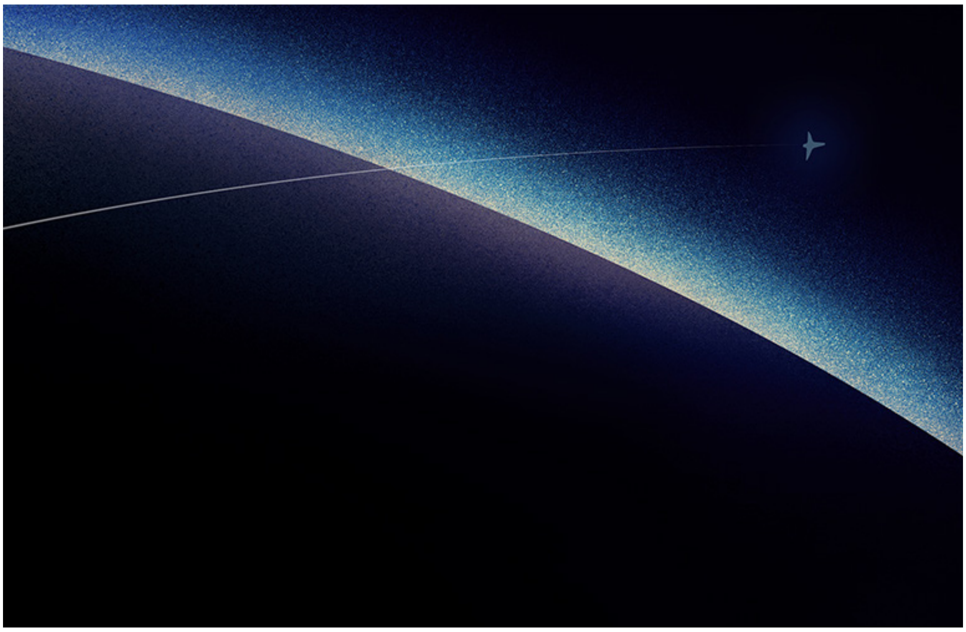


Fig. 47–48:

Simple 1–2 color illustrations of outer space, created for use by a technology company. This work helped inform the aesthetic of *Satellites*, particularly the use of color and orbital patterns. Source: Penn, H. (2013). *Space* [Illustration]. Retrieved from http://penn.pithytwigs.com/space

Discovered after *Satellites* had been finalized and sent to print, *Ground Truth* makes use of the same SATCAT data to create similar orbital pathways of active satellites. These orbital pathways are overlaid onto photographs taken in the Sonoran Desert in the Southwest United States, featuring concrete structures placed in the ground.

The concrete structures, of which there were originally 256, were built by the CIA and U.S. Air Force to help calibrate the very first imaging satellites in the 1960s.[61] The structures were all created to be exactly 60 feet in diameter, and were placed one mile apart on a grid, acting as calibration targets for early aerial and satellite imaging and mapping. Most satellite maps of Earth rely on camera calibration which was originally gleaned from these concrete targets. Each photograph in the *Ground Truth* series features an overlay of all the active satellites passing overhead and their orbital pathways, very much like *Satellites* does, but with a focus on active satellites only as opposed to active satellites and debris. The series offers a glimpse into how far we have come from the early days of spaceflight and satellite activity.

Fig. 49–51:

Images from the augmented photo series *Ground Truth*, which features photographs of concrete structures in the Sonoran Desert, and satellite tracks overhead. Source: Anand, J., & Sauer, D. (2017). *Ground Truth* [Photograph]. Retrieved from http://www.2circles.org/ground-truth.html

61 Anand, J., & Sauer, D. (2017). *Ground Truth Statement.* Retrieved from http://www.2circles.org/ground-truth-statement.html

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