CYBER SECURITY PROJECT

Job One for Space Force: Space Asset Cybersecurity

Gregory Falco

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BELFER CENTER
for Science and International Affairs

PAPER
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Cover photo: A set of NanoRacks CubeSats is deployed from the International Space Station, February 25, 2014. (NASA/iss038e056389)

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About the Author

Gregory Falco is a Research Fellow with the Belfer Center's Cyber Security Project at Harvard Kennedy School. He received his PhD in Cybersecurity from MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) and earned his master's degree from Columbia University and undergraduate degree from Cornell University. He is an expert in Industrial Internet of Things (IIoT) cyber-physical system security. His research focuses on analyzing cyber risk to critical infrastructure using AI planning, data science and qualitative methods. Much of his work has focused on the security of smart cities' industrial control systems used in critical infrastructure including electric grids, water networks and transportation systems. He has pioneered the field of Defensive Social Engineering—a toolbox of non-technical defenses that employs social engineering methods against hackers.

Greg is an Adjunct Professor at Columbia University where he teaches classes on machine learning, big data and smart cities. He is also the Co-founder and CEO of NeuroMesh, an IoT managed security and endpoint protection company that is piloting its technology with major utilities to secure the routing and smart metering infrastructure of the Smart Grid. Previously, Greg has worked as a security researcher for NASA's Jet Propulsion Laboratory on cutting edge AI-based risk assessment for mission critical IoT and was an executive at Accenture where he founded the Smart City Strategy Division. He will begin his postdoctoral studies at Stanford University in the Fall where he will teach courses on Cyber Risk.

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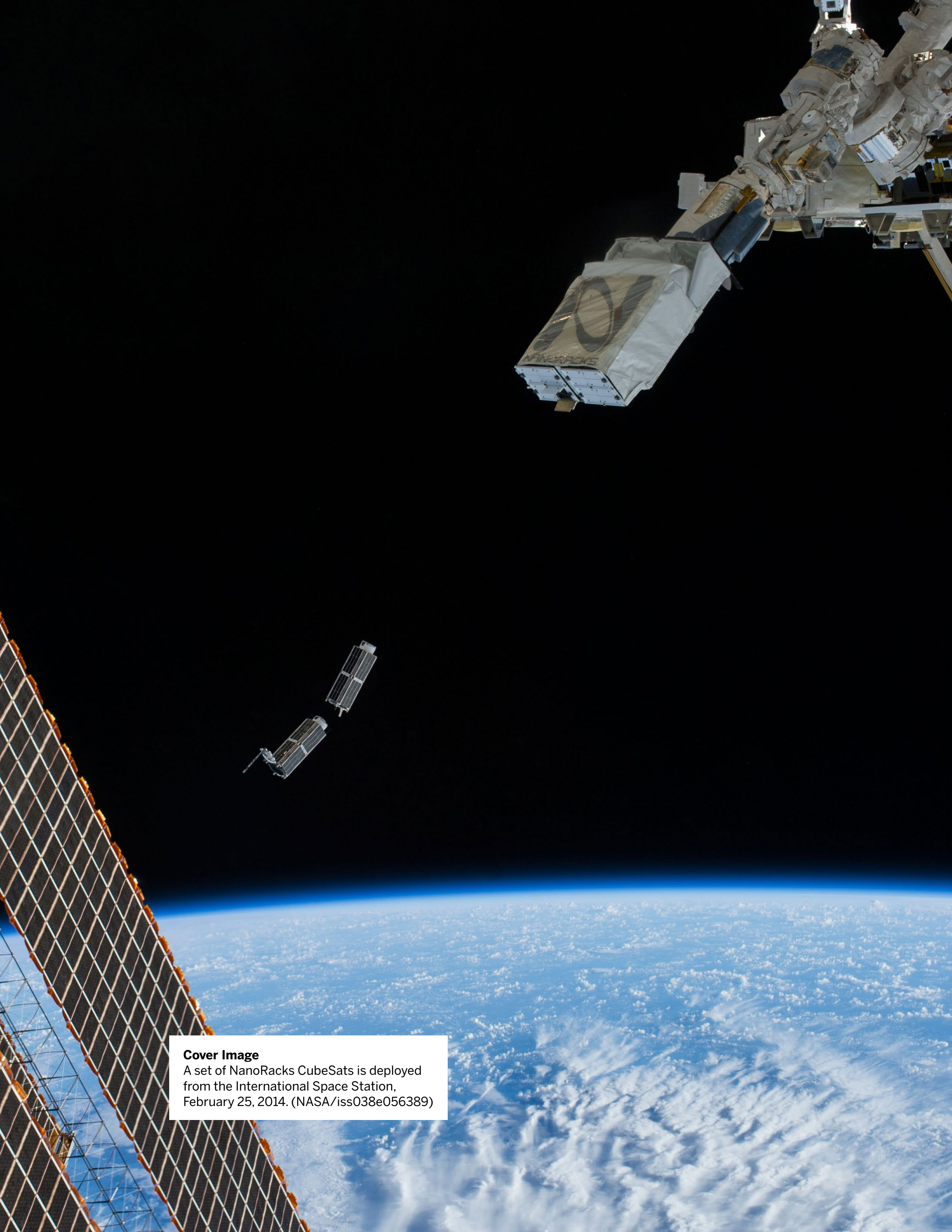


Cover Image
A set of NanoRacks CubeSats is deployed from the International Space Station, February 25, 2014. (NASA/iss038e056389)

Executive Summary

When we think about critical infrastructure, the first assets that come to mind include the electric grid, water networks and transportation systems. Further unpacking the definition of critical infrastructure, we consider industries such as agriculture, defense or the financial sector. However, we rarely think about where the underlying systems that enable technology functionality across these sectors physically reside, who developed the technology, and who can access and manage that technology.

Much of the United States' critical infrastructure relies on space systems. I define space systems as assets that either exist in suborbital or outer space or ground control systems—including launch facilities for these assets. Space asset organizations are organizations that build, operate, maintain or own space systems. Some examples of critical infrastructure's reliance on space systems are agribusiness' reliance on weather and climate satellites, the U.S. military's reliance on intelligence satellites, and various transportation industries' reliance on global positioning system (GPS) satellites. Several critical infrastructure sectors also rely on space systems for global communications. We also rely on space systems for scientific discovery, which often requires highly specialized and advanced equipment. Such equipment originally designed for scientific discovery is later used in critical infrastructure sectors upon further testing and commercialization of the intellectual property.

Despite efforts to improve the cybersecurity of critical infrastructure in the U.S., there has been little focus on cybersecurity for space systems. While security standards for critical infrastructure are often technically sufficient to deter many attacks, they remain a challenge to implement due to time and resource constraints.[1] Space systems, however, are more complex than critical infrastructure from a technology development, ownership and management perspective. Thus far, this

[1] "Trends in Security Framework Adoption: A Survey of IT and Security Professionals." Dimensional Research. 2016. https://static.tenable.com/marketing/tenable-csf-report.pdf.

has led to a lack of guidance in the form of standards that govern space system security and, ultimately, policies that enforce these standards.

I will first review some of the major cybersecurity threats to space systems and the potential motivations for why cyber criminals or nation states would be interested in compromising space systems. Next, I will evaluate the challenges for managing space system cybersecurity. I will then evaluate steps currently being taken by companies and government agencies to secure these systems. Finally, I will propose policy recommendations to streamline cybersecurity for space systems across the public and private sectors. A selection of these recommendations are below.

Space Asset Organizations should:

- Apply existing cybersecurity standards and best practices to space assets and where necessary, develop new, tailored standards for unique components of space assets;
- Assign security experts with distinguished expertise based on the function of each space asset and enable this resourcing by establishing cybersecurity as a mission line-item in budgets. For example, do not assign a server security expert to work on the security of a satellite endpoint. Instead, designate security experts with satellite endpoint knowledge to secure these systems;
- Develop and incentivize a cybersecurity culture that prioritizes security across the teams working on space assets. For example, gamify good security behavior, such as running an internal phishing program where top performers are rewarded;
- Use appropriate cybersecurity tools such as encryption or threat intelligence. Encrypt communications even if the data transmitted from satellites will ultimately be public and open source to better protect the integrity of that information (such as weather data); and
- Develop relationships with security researchers that allow for researchers to access company data and provide solutions to remediate vulnerabilities in the company's systems.

Policymakers should:

- Hold space asset organizations accountable for cybersecurity deficiencies in the components of space systems that they develop, operate, and own. For example, require all space asset organizations that contract with the government to comply with key performance parameters for system survivability that covers cybersecurity;
- Expand the Code of Federal Regulations for the Department of Defense-Defense Industrial Base Cybersecurity Activities (32 CFR Part 236) to include required reporting of cyber incidents by space asset organizations that are responsible for space assets that enable other critical infrastructure; and
- The Department of Homeland Security should create a space system Information Sharing and Analysis Center (ISAC) that requires participation from government agencies that rely on space assets and encourage participation of the private sector's space asset organizations.

The Space System ISAC should:

- Require disclosure of credible sector cyber threats to other space system organizations within a certain time period so that others have the chance to act on the intelligence;
- Document and maintain space system security best practices and encourage member organizations to implement these security protocols; and
- Cooperate with ISACs for oil/gas, electricity and emergency services to assess space system vulnerabilities that underpin terrestrial systems for these critical sectors, and work to remediate accordingly.

Why are space systems an attractive target?

The Opportunity Landscape for Hackers

Space systems are essential to and underpin the critical infrastructure that enables our global economy and military presence, and act as a central point of failure across various industries. A stealthy cyber attacker's goal is generally to minimize exposure and maximize impact. One may think that a hacker attempting to cripple U.S. commerce would first try to interrupt e-commerce companies such as Amazon.com, disrupt online payments through PayPal, or impede a credit card provider. However, these companies invest heavily in cybersecurity and are constantly monitoring their networks for fraudulent and mischievous activity. Further, there are several systems that would need to be compromised simultaneously to cause the infrastructure that enables each of these pillars of commerce to malfunction. From the cyber attacker's perspective, perhaps a simpler route to compromising U.S. commerce would be to target communications satellites that provide connectivity enabling point of sale credit card systems, inventory management, and even video conferencing services. Even more valuable might be targeting the operator of a series of satellites that enable such services.

Satellites and their associated ground control systems that enable underlying infrastructural support are a central point of failure for commerce and other industries. Without space systems, many industries cannot efficiently function. For example, natural gas distribution companies rely on satellites for communications from remote pipelines to understand the health of their systems. Hackers who compromise a communications satellite can cause pipe explosions if they inhibit maintenance calls from these remote pipes to the natural gas distributor command center. There are various attack pathways to inhibit the central point of failure of a space system- two of which are the manufacturer of the space asset equipment and the operator or management company of the space systems. The ability to impact multiple systems by compromising a central point of failure makes space systems attractive targets.

Space systems such as satellites and their controls are typically sophisticated pieces of equipment considering their communication, radiation hardening, and computing requirements. Despite this, cybersecurity standards for space assets are not regulated by any governing body and a lack of regulation means that satellites both lack common cybersecurity standards and may be used for cyberattacks with impunity/anonymity. This is unlike other industries such as electric systems that are regulated by the Federal Energy Regulatory Commission (FERC). In fact, regulation of satellites is generally weak. The International Telecommunication Union (ITU), a United Nations agency, regulates frequencies of satellite communications to prevent communication interference and registers the orbits of satellites, but beyond these areas, there are few standards. At this point, there are no agencies restricting the use of satellites and there is no governing body that monitors satellite useages. Because of this vacuum, it is possible that some satellites are being used as a base to launch cyber operations or for other nefarious cyber purposes.

While the lack of standards for such critical systems is a concern, the complexity of the supply chain required to create these systems also makes them attractive to hackers. Some systems will require multiple manufacturers with various specialties to develop multiple technologies and a system integrator to compile all the components to function as one. The multiple vendors required provide various access points for a hacker to gain access to a satellite. Each incremental vendor provides an additional opportunity to compromise a satellite. For these highly complicated systems, we would assume that stringent security protocols are in place. However, not all satellites are so sophisticated. A recent trend includes low-cost satellites being launched into orbit that use commercial-off-the-shelf (COTS) technology. These “cubesats” have a fairly low barrier to entry for development from a technical standpoint and are well-within budget of any major company (or wealthy hobbyist) to launch (generally under $100K). Considering the COTS nature of the satellite, it is likely that components such as open-source operating systems riddled with security vulnerabilities are central to these satellites’ function. There are considerable security concerns for these systems because: 1) the wide distribution of COTS products means that many people have access to the devices, so a hacker can extensively analyze the device for vulnerabilities, 2) COTS products need to be actively maintained and upgraded for security patches that are often not applied by users, and 3) anyone could have contributed to the code behind open-source technology, which means that vulnerabilities or backdoors to the software could be intentionally planted by adversaries. As of 2017, it was estimated that there were approximately 700 cubesats in orbit.[2] It is conceivable for a company to launch a cubesat to streamline operations on Earth and by doing so introduce vulnerabilities to their IT ecosystem. Government agencies are known to lease bandwidth on commercial satellites, and doing so could introduce vulnerabilities into military or other government agency IT ecosystems as well if the cubesat is not appropriately secured.[3] While it is unlikely this would be the first choice of an attacker to disable a satellite, it could even be possible for a malicious organization to hack a cubesat or small satellite with propulsion and direct it to collide with other satellites. Cubesat collisions are known phenomena. In one instance, the European Space Agency noticed a cubesat cut a hole in the solar panel for its Sentinel 1-A satellite.[4] This was an unintentional mishap, but one can imagine that a malicious actor could do much worse.

Space systems are attractive targets due to their ability to serve as a central point of failure to massive systems, their lack of security regulation, and their vast surface area of attack. Considering that so much U.S. critical infrastructure relies on space systems, it would be logical for hackers to attempt to compromise critical infrastructure via this means. Space systems do not need substantially different security systems than other critical infrastructure; however, they do need special attention for security because they often go overlooked. Because they act as underlying infrastructure for critical systems, they are not necessarily considered to be part of critical systems themselves and therefore are not subject to the same security standards. Further, as discussed more in depth below, cybersecurity responsibility for space systems is extremely convoluted compared to other industries, which leaves room for ambiguity regarding who should secure these vital systems and how they should be secured.

[2] Leonard David. “Sweating the Small Stuff: CubeSats Swarm Earth Orbit.” Scientific American. 2017. https://www.scientificamerican.com/article/sweating-the-small-stuff-cubesats-swarm-earth-orbit/.

[3] Ryan Schradin. “Government Space Leaders Look To Commercial Satellites for More Resilient Communications.” The Government Satellite Report. 2016. https://ses-gs.com/govsat/defense-intelligence/government-space-leaders-look-to-commercial-satellites-for-more-resilient-communications/.

[4] Tereza Pultarova. “Could Cubesats Trigger a Space Junk Apocalypse?” Space.com. 2017. https://www.space.com/36506-cubesats-space-junk-apocalypse.html.

What attacks have occured on these systems?

Space assets have already been compromised by nation states and criminal organizations. The most referenced attacks were mounted against government and corporate-backed space assets. These attacks demonstrate that even well funded space projects lack the appropriate cybersecurity to defend against hackers.

Among the most interesting attacks waged thus far against satellites had little to do with hackers' interest in compromising the space system, but rather the technology that was enabled by the space system. Kaspersky Labs discovered that the Russia-based cyber-espionage group, Turla, hacked their way into a satellite internet provider to hide cyber-espionage operations against countries ranging from the US to the former Eastern Bloc.[5] By using a ground antenna, Turla could detect IP addresses from satellite internet users and then initiate a TCP/IP connection from the stolen IP address. Turla can obfuscate their nefarious operations by leveraging the stolen IP satellite address. The attack is not easily detectable because the espionage operation does not need to perceivably impact the innocent user's performance; it depends on whether the hacker and the legitimate user are using the IP address simultaneously. Because both the victim and attacker's machines would have the same IP address, the attack will be stealthy and unlikely to be flagged by intrusion detection systems.

Independent of how stealthy space-based cyberattacks can be, they can cause serious damage to an end-user's operations. Imagine that hackers employ Turla's technique to target a remote electric substation. An attacker can intercept uplink or downlink packets from the victim's IP address or inject data to the user system connected to the IP address. Such a false data injection to an autonomous drone could result in an override of the system or even crash the aircraft.

Another space-based cyberattack compromised GPS systems, which rely on satellites to triangulate specific positions on Earth. Introducing noise

[5] Kaspersky's Global Research and Analysis Team (GReAT). "The Epic Turla Operation." SecureList. 2014. https://securelist.com/the-epic-turla-operation/65545/.

into the receiver spectrum of the GPS satellite can cause the failure of a GPS receiver on earth to provide a reading. This is a technique known as jamming. Russia has installed GPS jammers on over 250,000 cellular towers to disrupt the navigation of incoming missiles from the US.[6] While GPS jamming attacks have been used in the past and are not necessarily considered a cyberattack, GPS spoofing is a cyberattack because of the manipulation of the GPS signal. GPS spoofing is far more dangerous than jamming because it appears that the GPS is working as intended. The trust in the device is not broken for a spoof, which becomes dangerous when dealing with critical systems.

There are multiple ways to spoof a GPS satellite. One mechanism to do so is by compromising the satellite receiver and altering the output signal from the satellite. Another opportunity is via a false data injection attack where an adversary uses a GPS signal simulator (whose success will be limited because it cannot always trick the receiver) or uses a software-defined spoofer. Software-defined spoofers are more reliable. They work by inserting a barely detectable fake signal behind the true signal. Gradually, the power of the fake signal is increased to the point where the receiver thinks the fake signal is actually the real signal.[7] A system that can execute a software-defined spoof attack only costs about $1,000-2,000 to build, as demonstrated by Professor Todd Humphreys at the University of Texas, Austin.[8]

Attacks using software-defined spoofing are not just theoretical or conducted in a lab. In 2017, the US Maritime Administration reported the first GPS spoofing attack against over 20 ships in the Black Sea.[9] Correspondence between one of the impacted vessels and their command center reflects that over the course of the attack, the GPS position displayed on

[6] Andrew Dalton. "Russia Hopes to Block Cruise Missile Attacks with Cell Towers." Engadget. 2016. https://www.engadget.com/2016/10/17/russia-jamming-cruise-missile-attacks-with-cell-towers/.

[7] Alan Gatherer. "Lost in Space: How Secure is the Future of Mobile Positioning." IEEE ComSoc Technology News. 2016. https://www.comsoc.org/ctn/lost-space-how-secure-future-mobile-positioning.

[8] Colin Lecher. "Texas Students Hijack a U.S. Government Drone in Midair." Popular Science. 2012. http://www.digitaljournal.com/article/327529.

[9] Maritime Administration. "2017-005A-GPS Interference-Black Sea." US Department of Transportation. 2017. https://www.marad.dot.gov/msci/alert/2017/2017-005a-gps-interference-black-sea/.

their navigation tool sometimes showed "lost GPS fixing positon."[10] At one point during the attack, the spoofed location showed the ship was located near the Gelendzhik airport, but was in fact 25 nautical miles from the reported location. According to a non-profit organization called Resilient Navigation and Timing, which monitors GPS incidents, anecdotal spoofing reports are not uncommon in Russian waters.[11] It is widely speculated that another attack of this type was used by the Iranians to capture a US drone in December 2011.[12] In September 2011, Iranians claimed they mastered a new technique to compromise aircrafts via GPS spoofing. This technique was demonstrated when they successfully captured an American RQ-170 Sentinel drone by reconfiguring the coordinates of the GPS signal to make the drone land in Iran instead of its base in Afghanistan.[13] The US military blamed the capture on a malfunction, but were unable to explain how the Iranians received the drone intact.[14]

These incidents represent a small sampling among many other reported cyberattacks on space assets.[15] Beyond actual cyberattacks, "thought experiments" and demonstration attacks on space assets have been referenced in various reports.[16] Given that there have been so many cybersecurity incidents involving space assets, why has so little work been done to secure these assets?

[10] Dana Goward. "Mass GPS Spoofing Attack in Black Sea?" The Maritime Executive. 2017. https://www.maritime-executive.com/editorials/mass-gps-spoofing-attack-in-black-sea; http://www.insidegnss.com/node/5555.

[11] Lisa Vaas. "Suspected Mass-Spoofing Of Ships' GPS In The Black Sea." Naked Security, 2017, https://nakedsecurity.sophos.com/2017/09/26/suspected-mass-spoofing-of-ships-gps-in-the-black-sea/.

[12] Lisa Vaas. "Drone Hijacked By Hackers From Texas College With $1,000 Spoofer." Naked Security. 2012. https://nakedsecurity.sophos.com/2012/07/02/drone-hackedwith-1000-spoofer/.

[13] Scott Peterson. "Exclusive: Iran Hijacked US Drone, Says Iranian Engineer." The Christian Science Monitor. 2011. https://www.csmonitor.com/World/Middle-East/2011/1215/Exclusive-Iran-hijacked-US-drone-says-Iranian-engineer.

[14] Ibid.

[15] D.J. Byrne, David Morgan, Kymie Tan, Bryan Johnson, Chris Dorros. "Cyber Defense of Space-based Assets: Verifying and Validating Defensive Designs and Implementations." Procedia Computer Science. Volume 28. 2014 http://www.sciencedirect.com/science/article/pii/S1877050914001276.

[16] Ruben Santamarta. "A Wake-up Call for SATCOM Security." IOActive. 2014. http://www.cs.tufts.edu/comp/116/archive/fall2016/rhutchins.pdf; https://ioactive.com/pdfs/IOActive_SATCOM_Security_WhitePaper.pdf.

Why are space assets so vulnerable today?

Originally, space assets, like all other technology, were analog devices. These systems did not present the same opportunities for hacking because they lacked software with code vulnerabilities and the ability to access the system remotely. As technology moved into the digital age, space assets became digitized as well. Like most systems of the time, cybersecurity was generally not considered and certainly not prioritized. For example, when TCP/IP was created, the protocol's security was not seen as an issue. Even when security was required and considered, manufacturers still did not take cybersecurity seriously. A case that illustrates this is problem is the Iridium satellite constellation, which provided GPS capabilities to the Pentagon. When the constellation was created, no special cybersecurity parameters were deployed because engineers thought the technology was too advanced for a hacker to compromise.[17] This naiveté was not unique to the Iridium constellation developers, as security was not considered a concern for decades into the early 2000s for many industries. For example, industrial control system operators and manufacturers cite the proprietary protocols in their system and insist that the protocol would be too complicated and obscure to crack.[18] In terms of cybersecurity, space assets were not any different from digital assets on earth.

As data server manufacturers and operators started to care about security in the early 2000s after cyberattacks against these systems were made public and impacted their business, space assets began to lag behind. Despite most industries adopting standard encryption schemes for data storage and transfer in the 90s[19], space technology designers and manufac-

[17] J.M. Porup. "It's Surprisingly Simple to Hack a Satellite." Motherboard. 2015. https://motherboard.vice.com/en_us/article/bmjq5a/its-surprisingly-simple-to-hack-a-satellite.

[18] "Recommended Practice: Improving Industrial Control System Cybersecurity with Defense-in-Depth Strategies." Industrial Control System Cyber Emergency Response Team. 2016. http://www.verizonenterprise.com/verizon-insights-lab/VES/obscurity-no-more-4-steps-to-securing-the-ot-environment-for-manufacturing.

[19] Jinwoo Hwang. "The Secure Sockets Layer and Transport Layer Security." IBM Developer Works. 2012. https://www.sslshopper.com/what-is-ssl.html.

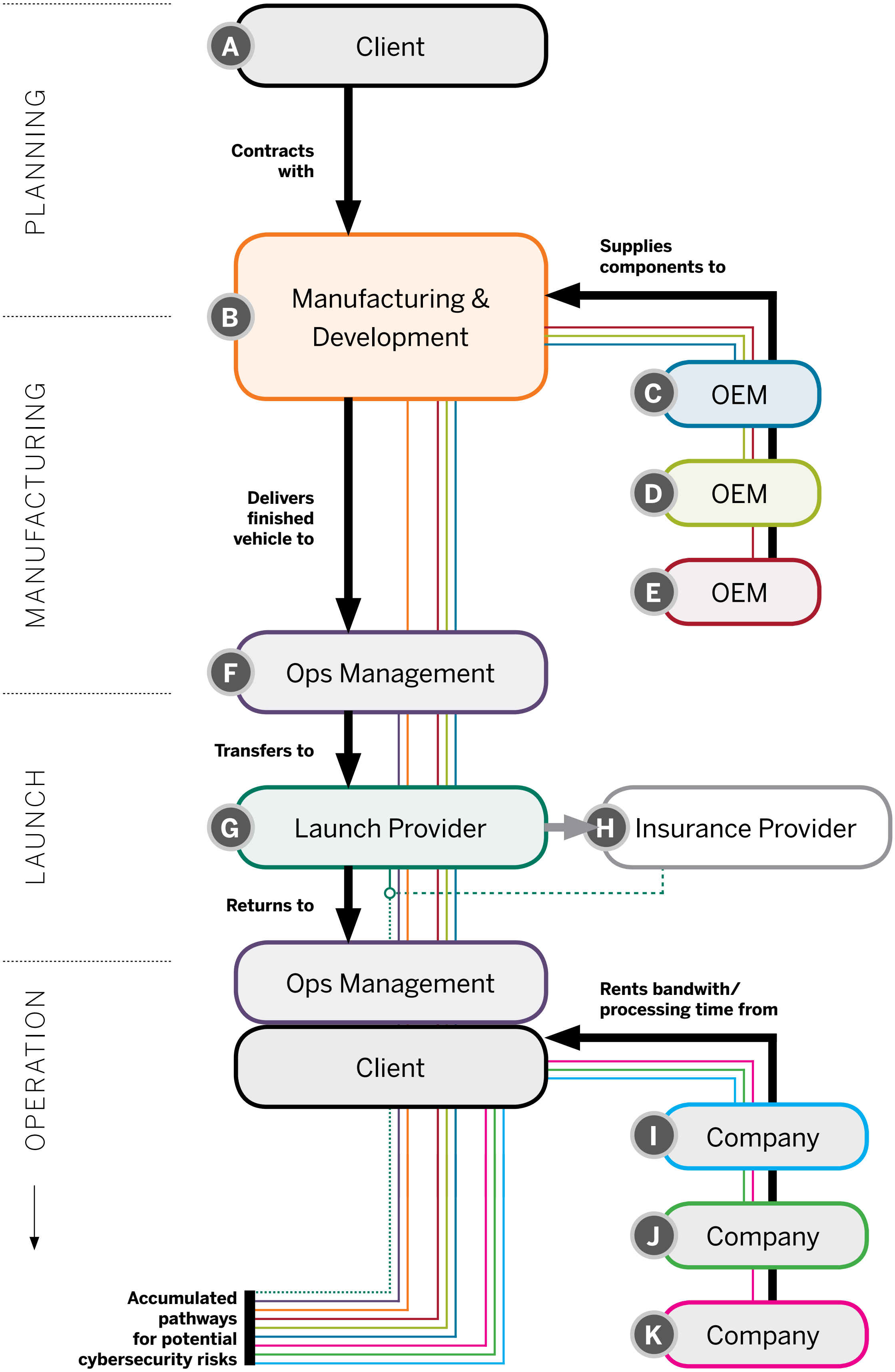
turers seemed to resist the movement toward security.[20] We can speculate that the resistance could be a function of lower profit margins for space systems compared with commercial products or defense systems. Also, some security techniques, such as encryption, require more processing power to function. On many space systems, processing power and bandwidth is a precious resource and other functions are given priority. Some space systems are developed as a "labor of love" and/or "in the name of science" and the developers of the technology do not even think about why someone would want to hack their project. Because of the open-source nature of data published by NASA and other space agencies, it may have been unclear what proprietary information there even was to secure.

Some of the lag relating to space asset security can be explained by the complexity of the supply chain and vendor ecosystem for the big corporate, government, and military-funded systems. The specialized parts needed for space assets are not all created by one manufacturer. In fact, to keep costs down, NASA and other space technology developers purchase components from catalogs of approved vendors around the world.[21] The approval process for these vendors does not necessarily specifically include cybersecurity vetting standards and instead concerns physical quality control. When NASA purchases a part from a vendor, they have little control over which technician developed the printed circuit board (PCB) or what software engineer wrote the code for a given component. This lack of insight introduces considerable cybersecurity risk. In addition to vendors being vulnerable across the system supply chain, space asset organizations generally work with several research centers who may possess vulnerabilities. Collaborations across multiple partners exacerbate potential security issues.

[20] Paul Martin. "NASA Cybersecurity: An Examination of the Agency's Information Security." Testimony before the Subcommittee on Investigations and Oversight, House Committee on Science, Space, and Technology. 2012. https://oig.nasa.gov/congressional/FINAL_written_statement_for_%20IT_%20hearing_February_26_edit_v2.pdf.

[21] Michael Sampson. "NASA Parts Selection List." NASA Electronic Parts and Packaging Program. 2016. https://nepp.nasa.gov/npsl/npsl_UsePolicy.htm.

Figure 1: **Cybersecurity risks and responsibility pathways for an example satellite project**



Complex supply chains related to space assets make it challenging to discern who should be operationally and financially responsible for the cybersecurity of a system at various point of the space asset's lifecycle. The challenge of the space asset supply chain is caused by the complexity of development, management, use and ownership environment of space assets. Unlike most critical infrastructure sectors, space assets are not owned by the same organizations that manage the infrastructure which results in questions related to liability if they are attacked. Figure 1 depicts a graphic representing the complex landscape for cybersecurity responsibility.

As shown, company **A** may commission the development of a satellite with company **B** that then assumes the cybersecurity responsibility of the satellite. Company **B** then outsources components of that satellite development to companies **C**, **D,** and **E,** who own their own component of the cybersecurity responsibility of the satellite. When company **B** completes the development of the satellite and delivers it to the owner (company **A**), company **F** is then contracted to manage the operations of the satellite (Company F then assumes operational cybersecurity responsibility of the satellite). Company **F** then commissions company **G** to launch the satellite into space. Company **G** assumes cybersecurity responsibility during the launch process. The liability for this cybersecurity responsibility is often shifted to an insurance provider company, **H**. Once the satellite is in orbit and operational, the management company (**F**) then resumes cybersecurity responsibility for the operations of the satellite. Often, the owner of the satellite (company **A**) will want to maximize the utility of the satellite to improve profitability and so will lease the use of bandwidth or processing on the satellite to other companies **I**, **J**, **K**, etc. Because of this complex ecosystem of owner, developer, operator and user cybersecurity responsibility, there are many opportunities for an adversary to gain access to the satellite.

Not only are there many stakeholders involved in the space asset development lifecycle, but the lifespan of the asset itself is extensive and complicated. Space missions can last decades and because of this, security concerns can be exacerbated from legacy systems that are unpatched. Not dissimilar to industrial control systems, space assets are built to last and because they are functional in the field for such long periods and are mission critical, system downtime is not an option. This makes space assets difficult if not impossible to patch for security flaws once they are discovered.

Finally, the institutional design of space system organizations causes security challenges. To properly secure a system, it is important to understand how the system works and the various opportunities for a hacker to disrupt the asset. Because this is so, the security experts that are knowledgable in data management, servers, and internal networks for traditional IT infrastructure likely are not the same experts who fully understand a specialized satellite or ground control system for a deep space asset. Despite this, most space system organizations' security groups are not set up to distinguish between internal IT infrastructure and specialized space systems. This could leave space assets vulnerable because specialists that understand their function are not attending to their security. Also, because of the broad responsibilities of the security team—spanning both IT and space assets-the security experts are spread thin.

Part of the resourcing concern across space asset organizations is that cybersecurity is typically not a line-item in mission budgets. This makes it more difficult to justify why extra resources should be spent on security personnel who are experts in specific mission systems. Without allocated budget for cybersecurity tasks, system engineers are left to figure out security needs for their space assets. Unfortunately, they are not necessarily adequately trained to be seeking out security flaws in their designs and are also time-constrained, which could result in poor attention to system security.

Another challenge at the organizational level is employee access control to sensitive information. Exacerbating this issue for space assets are the many niche skills required to develop these systems and the resulting number of resources needed to complete a project. Widespread access to develop the space asset increases the need for control procedures such as access management. NASA employees have continuously been subjected to phishing attacks, which, when successful, reveal sensitive information that can be used to compromise space assets to attackers.[22] The sheer volume of people that need access to such sensitive data is an ongoing risk for such organizations and begs the need for stricter operating and access standards.

Despite the historical reasons why the cybersecurity of space assets has lagged behind other kinds of critical infrastructure, such as energy systems, which are regulated by NERC and have robust industry standards, and financial institutions, which are regulated by the Security and Exchange Commission (SEC), there are relatively few technical obstacles to better cybersecurity. This poses the question: how are space assets being secured today to combat the growing cyber threat?

What is being done today to secure these systems?

Among the space industry community, the lack of attention to cybersecurity is acknowledged; however, the responses to the cybersecurity threats have been variable. An audit of NASA in FY 2015 revealed the need for a revamping of their cybersecurity standards and protocols. The audit cited several attacks on NASA space assets, which were not publically disclosed, as the driver for the call for reform.[23] NASA's efforts are not necessarily representative of the broader space industry's cybersecurity awareness and efforts—however, smaller organizations working on satellites look to NASA for standards and best practices. More established private space companies such as SpaceX or Blue Origin have no public comments on their cybersecurity posture. There have been calls for more discussion from the public on how SpaceX and others plan to address cybersecurity in the future.[24]

NASA has taken several steps to improve security around space assets. With this said, there are considerable opportunities for improvement. First,

[22] John Sprague. "Collaboration that Pays NASA Back." NASA IT Talk. 2012. https://www.hq.nasa.gov/office/itcd/notices/010410-1.htm.

[23] Paul Martin. "NASA's Management of the Deep Space Network." NASA Office of Audits. 2015. https://oig.nasa.gov/audits/reports/FY15/IG-15-013.pdf.

[24] Zulfikar Abbany. "SpaceX's Starlink satellite internet: It's time for tough talk on cyber security in space." Deutsche Welle. 2018. http://www.dw.com/en/spacexs-starlink-satellite-internet-its-time-for-tough-talk-on-cyber-security-in-space/a-42678704.

NASA has begun implementing stricter access control policies across their providers and engineers. This will help guard against some of the phishing attacks used against NASA employees in the past that steal credentials and access valuable intellectual property.

Second, NASA has created teams across their space asset development centers that specifically work with the security of their missions' systems. Previously, the Office of the Chief Information Officer (OCIO) was responsible for all cybersecurity across NASA. However, OCIO teams could not fully focus their attention on both the server infrastructure security of NASA's labs and mission systems, respectively. To address this challenge, NASA's Jet Propulsion Laboratory (JPL) created the Cyber Defense Engineering and Research Group (CDER). CDER's goal is specifically to address mission systems (such as the Mars Science Lab or the Europa Lander), which often have unique cybersecurity requirements from traditional firewalled data servers. Developing specialized teams that have unique expertise in mission systems enables customized analysis and protection for these space assets in ways that traditional security teams protecting servers and data would not. Some of CDER's work aims to develop tools and methodologies that apply across multiple mission systems to reduce costs and security operations.

Finally, NASA has begun encrypting data while it is stored and during transfer. Recently, at the end of 2016, AT&T encrypted NASA's Deep Space Network (DSN), which is the foundation of communication infrastructure for technology such as the Mars Rover.[25] Consistent with the previous section's explanations of why space assets lag behind other assets in cybersecurity, AT&T encrypted the DSN only after a report on how to hack into the Mars Rover appeared on the Internet.[26] Encryption provides private communications that are only visible to others with the cryptographic key. Such encryption will become a first line of defense against hackers aiming to hijack the DSN or listen in on communications sent over this multi-billion-dollar, long-range communication network.

[25] "AT&T Powers NASA's Deep Space Network." AT&T. 2016. http://about.att.com/story/att_powers_nasa_deep_space_network.html.

[26] Sebastian Anthony. "Could you hack into Mars rover Curiosity?" ExtremeTech.com. 2012. https://www.extremetech.com/extreme/134334-could-you-hack-into-mars-rover-curiosity.

NASA JPL's CDER Group is also working with university researchers at MIT to conduct penetration tests on mission system software. Increasing engagement with the broader security research community will considerably improve mission system security for space assets. CDER is also proactively working to establish a security culture at JPL. A security culture is one of healthy digital skepticism, where employees "think before they click" and do not trust all digital content at face value. CDER kick started building a security culture by starting a lighthearted game called Donuts. When a CDER Group member leaves their computer unlocked, another CDER teammate sends an email from the unlocked computer writing "Donuts" in the subject line. If this note is sent, the compromised computer user needs to buy the team donuts. The teams keep track of the number of donuts owed by each team member thereby incentivizing teammates to lock their machines when they step away. At first, the team was getting their fair share of donuts daily, but as security awareness grew the donuts stopped coming. This game has expanded to other teams at JPL, thereby helping to establish a security culture of constant security awareness.

Like NASA, the private space asset industry is currently improving its security, but as previously mentioned, it is impossible to evaluate many private sector companies who are not transparent regarding their cybersecurity efforts. Penetration testers, ethical hackers and security researchers are constantly finding holes in various satellite network systems and asking the responsible party to fix the vulnerabilities. Unfortunately, these vulnerability notifications often go ignored due to manufacturers' lack of bandwidth to address the issues or mistrust of the hackers. The lifecycle complexities and associated liability questions discussed earlier further complicate fixing vulnerabilities. If ignored, the ethical hackers generally follow responsible reporting procedures and expose the vulnerability to the public following a period of time after notifying the vendor. By publicly announcing the threat, the ethical hackers intend to garner large-scale attention to the problem and force the vendor to fix the issue. This was the case with the Iridium satellite owners who asserted their systems were extremely difficult to hack .[27] Only after ethical hackers announced their vulnerabilities and

[27] J.M. Porup. "It's Surprisingly Simple To Hack A Satellite." Motherboard. 2015. https://motherboard.vice.com/en_us/article/bmjq5a/its-surprisingly-simple-to-hack-a-satellite

embarrassed the company did Iridium take steps to improve the security of their communication network.

Unlike GPS satellites that can be detected and penetration tested without direct access to the space asset, other private industry space asset security is inaccessible and therefore not testable by the security community. For example, SpaceX, Virgin Galactic or other space asset developers, owners and operators do not make their technology readily available for security researchers to test. This is probably because they are concerned that their sensitive code or information will fall into competitors' hands. Another reason is that private space asset developers are concerned about what the security researchers will find and fear that if it is publicly disclosed, that can ruin their companies. Further, there is not any required disclosure or reporting on cybersecurity testing procedures from these companies and as a result it is difficult for the security community to evaluate the cybersecurity of these space assets. Again, the theme of vulnerability disclosure liability and the risk of releasing technology for testing is substantial, which is a major barrier to transparency regarding space asset security.

Neither public nor private space asset organizations are at a complete standstill concerning their cybersecurity efforts, as we previously described with the NASA JPL work on building a security culture. However, there are considerable gaps to the space asset security posture compared with other critical infrastructure sectors, and these must be addressed. The steps for improvement are not uniform for private industry and government organizations, as described below.

Recommendations

What can space asset organizations do?

Organizations developing space assets are largely unregulated for cybersecurity purposes. The lack of specific space asset cybersecurity requirements necessitates a considerable degree of self-policing. Without mandatory standards, space asset organizations can improve their security either individually or collectively. What follows are some options to consider:

- *Employ existing cybersecurity standards and develop new standards for space systems where needed.* There is no lack of cybersecurity standards and best practices available for developers to follow when attempting to design and develop secure systems. Many of these standards, like the National Institute of Standards and Technology (NIST) Cybersecurity Framework, are well-documented and widely adopted in some form.[28] Most space systems' security can benefit from using these standards. In some cases, these standards may not apply for the specific technologies used in space systems. For these systems, space asset organizations should create new space asset-specific standards and best practices so that security can be applied consistently across the organization. Vendors of space asset organizations should also be held to these standards. This should involve the explicit testing and demonstration that vendors to these organizations conform to the security standard in place for the space asset organization.
- *Establish cybersecurity capabilities for mission systems and internal network/server systems.* Similarly to what was done at NASA JPL, it is important to establish separate cybersecurity specialists for mission systems and internal networks/server systems. The distinction between the two systems are operational technology versus information technology—each one has very different operating and security requirements and need to be addressed accordingly.

[28] Nicole Cieslak. "NIST Cybersecurity Framework Adoption on the Rise." Tenable. 2016. https://www.tenable.com/blog/nist-cybersecurity-framework-adoption-on-the-rise.

A security expert who knows how to manage firewall settings for servers is not necessarily the best security expert to deal with small microprocessors or operational technology systems. Security expertise should be specialized so that the right cybersecurity strategies are being employed for the particular function and threats to the system. To be able to allocate resources to mission system cybersecurity, that should be listed as a line-item in mission budgets.

- *Build a security culture.* Establishing a security culture where all those who work on space assets focus on cybersecurity matters rather than relying entirely on a designated cybersecurity team is also important. This could begin as simply as starting the "Donuts" game. Rewarding good cybersecurity behavior or using the traditional "name and shame" approach to punishing bad cybersecurity practices could help to encourage the security culture.

- *Utilize appropriate security tools that are available.* Space asset organizations should encrypt all satellite communications and space asset data where possible. Modern encryption schemes provide a cost-effective and rather simple security measure to accomplish without much computational overhead. Some space asset organizations do not feel the urgency to encrypt satellite communications due to the public, open-source nature of the data flowing across these systems. However, encrypting the data is still important to maintain the integrity of the communications so that the information can ultimately be useful for the public. Space asset organizations should also invest in "threat intelligence" tools so that they can consistently maintain situational awareness regarding the latest cyber technical and organizational threats.

- *Cooperate with security researchers. S*pace asset organizations can collectively work with ethical hackers and university researchers to conduct penetration tests of systems. This would provide a low-cost resource to space asset organizations seeking to improve their cybersecurity posture. A relationship with ethical hackers and university researchers can facilitate not only the discovery of vulnerabilities for critical space systems but also the remediation of these security holes. Many organizations establish bug bounty programs for security researchers to identify vulnerabilities in systems, but these often have limited success. One reason for this limitation is that bug bounty programs do not allow any privileged system access. This limits the researchers' abilities to find deeper bugs and security vulnerabilities that are not at the surface layer of the exposed system. Another challenge with the traditional approach to bug bounty is that after the bugs are identified, there are too many for the organization's security team to patch or remediate in a timely fashion, thereby exposing the organization to additional risk during this period. Partnering with security researchers to not only discover vulnerabilities but also fix security issues can considerably improve security outcomes. As we have already described, there are barriers to establishing a transparent and substantial relationship with security researchers. For example, providing privileged access to security researches could expose the space asset organization to liabilities. The third party could unintentionally disclose private data or vulnerabilities to the public. This could cause a public relations disaster and provide an invitation to hackers to exploit vulnerabilities.

These are some actions that space asset organizations can take without national policy or legal guidance. However, some of these cybersecurity improvements can be enabled through policy shifts concerning space assets.

What can policymakers do?

To date, congress has provided little guidance in terms of enabling cybersecurity across sectors. One of the few examples includes the Cybersecurity Information Sharing Act (CISA) which was signed into law in late 2015 by President Obama. CISA is meant to help facilitate information sharing between the government and the private sector by limiting the liability of the private sector for certain attack disclosure.[29] Congress should develop more laws that could be specifically relevant to space assets. Recommendations concerning these laws follows.

- *This is Urgent. Act quickly. Be proactive, not reactive.* Do not wait to pass a law on space cybersecurity until there is a WannaCry (major ransomware attack that compromised healthcare systems around the world) or Mirai (IoT attack that took down a major DNS provider on the East Coast resulting in downtime for websites such as Facebook, Twitter and Reddit) equivalent for Space. It seems that action only occurs when a disaster strikes. A space cyberattack can have serious consequences as detailed previously and we cannot wait until something happens to pass legislation protecting these critical systems.
- *Clarify critical infrastructure security requirements to include underlying systems.* Currently, policy concerning critical infrastructure security does not require third-party, enabling infrastructure to also comply with the same requirements. Space systems should be held to the same standards of the critical infrastructure on which they rely.
- *Assign responsibility and liability for cyber.* Cybersecurity responsibility and associated liability for a breach should be clarified and assigned for space asset organizations. An important component of cybersecurity legislation currently under review concerns the liability of technology developers, owners and operators. In January 2017, the FTC sued D-Link for the vulnerability in their routers

[29] Brad Karp. "Federal Guidance on the Cybersecurity Information Sharing Act of 2015." Harvard Law School Forum on Corporate Governance and Financial Regulation. 2016. https://corpgov.law.harvard.edu/2016/03/03/federal-guidance-on-the-cybersecurity-information-sharing-act-of-2015/.

leading to the widespread Mirai botnet attack in October 2016.[30] This was the first time a manufacturer was sued for the cybersecurity failures of their devices. Legal guidance concerning where liability falls will encourage the responsible party to take the necessary measures to secure their systems. Today's lack of clarity around liability for the space asset ecosystem results in poor accountability and inaction to secure these important systems.

- *Make space asset organizations accountable for cybersecurity.* All government contracts with space asset organizations should require the contractor to comply with key performance parameters (KPPs) pertaining to cybersecurity. Today, cybersecurity KPPs are a subcomponent of system survivability KPPs. Cybersecurity KPPs should be firmly enforced for all government contracts.

- *Expand 32 CFR 236 to include space asset organizations.* Currently, the defense industrial base is required to report all cyber incidents that have affected or could affect national security under the Department of Defense-Defense Industrial Base Cybersecurity Activities Regulation[31]. Considering the critical posture of space systems and the U.S. reliance on these assets for both national security and critical infrastructure, space asset organizations should be included under this ruling. This would improve cybersecurity transparency between the government and space asset organizations.

- Establish a Space System Information Sharing and Analysis Center (ISAC). Government agencies such as the Department of Homeland Security (DHS) could play a crucial role as a convener for public and private sector entities that work with space systems. The DHS could become an important facilitator for this sector's efforts to improve cybersecurity by creating a Space System Information Sharing and Analysis Center. The DHS should require participation of government agencies that work with space systems ranging

[30] Ari Lazarus. "FTC sues D-Link over router and camera security flaws." Federal Trade Commission. 2017. https://www.consumer.ftc.gov/blog/2017/01/ftc-sues-d-link-over-router-and-camera-security-flaws.

[31] Defense Department. "Department of Defense (DoD)-Defense Industrial Base (DIB) Cybersecurity (CS) Activities." Federal Register. 2015. https://www.federalregister.gov/documents/2015/10/02/2015-24296/department-of-defense-dod-defense-industrial-base-dib-cybersecurity-cs-activities.

from the Department of Defense (DoD) to NASA to participate in the Space System ISAC. This would provide an incentive for private sector space asset organizations to also join. If 32 CFR 236 were expanded to include space asset organizations, the Space System ISAC could be made compulsory through this requirement. Sharing threat information across space system agencies and space asset organizations would be a logical step to improve the security posture of the sector. Some agencies or private organizations may be much further ahead in securing systems than others and sharing insights will help all ISAC members involved.

What can a Space System ISAC do?

Sharing threat information across space system agencies and space asset organizations would be a logical step to improve the security posture of the sector. Some agencies or private organizations may be much further ahead in securing systems than others and sharing insights will help all ISAC members involved. The recommendations for what a Space System ISAC should are as follows.

- *Encourage collaboration among space-relevant organizations.* The DHS should require participation of government agencies that work with space systems ranging from the Department of Defense (DoD) to NASA to participate in the Space System ISAC. This would provide an incentive for private sector space asset organizations to also join. If 32 CFR 236 were expanded to include space asset organizations, the Space System ISAC could be made compulsory through this requirement. Sharing threat information across space system agencies and space asset organizations would be a logical step to improve the security posture of the sector. Some agencies or private organizations may be much farther ahead in securing systems than others and sharing insights will help all ISAC members.
- *Establish information sharing requirements.* The Space System ISAC should require member entities to disclose vulnerability and attack information to one another within a predefined period. This would

be in the spirit of the UK's General Data Protection Regulation (GDPR) that requires an organization to disclose when personally identifiable information is breached within 72 hours of discovery.[32]

- *Document and maintain space system cybersecurity best practices and standards.* Member organizations should share internal or contractor standards for cybersecurity in a manner that does not release sensitive information. A master list of best practices should be shared across the Space System ISAC and curated. Member organizations can comment on the merits of the best practices and cater existing cybersecurity standards to be highly relevant to the idiosyncrasies of space systems.
- *Cooperate with ISACs for other critical infrastructure sectors that rely on space systems*. Because space systems underpin other sectors, certain threat information for space systems should be shared with the relevant sectors that might be affected if an attack occurs. The Space System ISAC should work with the oil/gas, electricity and emergency services ISAC to communicate threats that are relevant to these critical infrastructure and services. The potentially affected critical infrastructure organizations could then work with the space asset organizations to remediate the vulnerability where appropriate.

[32] "General Data Protection Regulation." https://gdpr-info.eu/art-33-gdpr/.

Conclusion

Space assets are underlying systems on which most critical infrastructure in the U.S. relies. Researchers, policymakers and engineers are increasingly concerned with the cybersecurity of critical infrastructure, but fail to include the space assets that enable these systems. Cybersecurity challenges will only become more substantial as technology continues to evolve and attackers will always find the weakest link to penetrate a target system. Today, space assets are that weakest link. Space asset organizations must not wait for policymakers to take action on this issue as there are several steps that could be taken to secure their systems without policy guidance. With this being said, it is the responsibility of policymakers to include space assets when addressing which technologies require cyberdefense to enable our country's continued digital "manifest destiny." It is time to fill the vacuum of space asset cybersecurity policy.

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