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# THESIS

**GPS: PUBLIC UTILITY OR SOFTWARE PLATFORM?**

by

Marc A. Thibault Jr.

September 2016

Thesis Advisor: Rodrigo Nieto-Gomez
Second Reader: Lauren Wollman

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The Global Positioning System (GPS), a satellite navigation system, is critical to the United States' (U.S.) national and homeland security. The U.S. has made GPS resilient to interruption by flying more satellites than required, dispersing its infrastructure, and increasing its signals. Despite these efforts, there is concern the U.S. may not be able to overcome disturbances in GPS's operations. Limitations in GPS data and the policy literature prevent the full quantification of exactly how vulnerable GPS is to service interruption.

This thesis used constant comparison analysis to examine how a shift in conceptual lens from viewing GPS as public utility to viewing it as a software platform has changed our understanding of its criticality, resilience, and vulnerability. This methodology overcomes research limitations by using GPS system design, operations, and policies as its data sources. The public utility lens reveals the U.S. has increased GPS resilience through system design and redundancies. The software platform lens shows the U.S. further increased GPS resilience by adding navigation signals. Together, the lenses indicate manufacturers, applications developers, and users are constraints to increasing GPS's resilience. Additional data, models, and research are required to inform policies and decisions to further improve GPS's resilience.


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# GPS: PUBLIC UTILITY OR SOFTWARE PLATFORM?

Marc A. Thibault Jr.
U.S. Coast Guard, Program Analyst
B.S., United States Coast Guard Academy, 1994
MPP, American University, 1998
Ph.D., George Mason University, 2004

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**September 2016**

Approved by: Rodrigo Nieto-Gomez
Thesis Advisor

Lauren Wollman
Second Reader

Erik Dahl
Associate Chair of Instruction,
Department of National Security Affairs

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# ABSTRACT

The Global Positioning System (GPS), a satellite navigation system, is critical to the United States' national and homeland security. The U.S. has made GPS resilient to interruption by flying more satellites than required, dispersing its infrastructure, and increasing its signals. Despite these efforts, there is concern the U.S. may not be able to overcome disturbances in GPS's operations. Limitations in GPS data and the policy literature prevent the full quantification of exactly how vulnerable GPS is to service interruption.

This thesis used constant comparison analysis to examine how a shift in conceptual lens from viewing GPS as public utility to viewing it as a software platform has changed our understanding of its criticality, resilience, and vulnerability. This methodology overcomes research limitations by using GPS system design, operations, and policies as its data sources. The public utility lens reveals the U.S. has increased GPS resilience through system design and redundancies. The software platform lens shows the U.S. further increased GPS resilience by adding navigation signals. Together, the lenses indicate manufacturers, applications developers, and users are constraints to increasing GPS's resilience. Additional data, models, and research are required to inform policies and decisions to further improve GPS's resilience.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ASD(NII) | Assistant Secretary of Defense for Command, Control, Communications, and Intelligence |
| CBO | Congressional Budget Office |
| CORS | Continuously Operating Reference Stations |
| DOD | Department of Defense |
| DHS | Department of Homeland Security |
| DOT | Department of Transportation |
| EU | European Union |
| GAO | General Accounting Office |
| GDGPS | Global Differential GPS |
| GPS | Global Positioning System |
| IGS | International Global Satellite Navigation Service |
| JPL | Jet Propulsion Laboratory (California Institute of Technology) |
| LORAN | Long Range Navigation |
| NAPA | National Academy of Public Administration |
| NOAA | U.S. National Oceanic Atmospheric Administration |
| NSATC | National Science and Technology Council |
| NRC | National Resource Council |
| OMB | Office of Budget Management |
| PNT | National Space-Based Positioning, Navigation, and Timing Advisory Board |
| RAE | Royal Academy of Engineering |
| SA | selective availability |
| SCOT | social construction of technology |

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# EXECUTIVE SUMMARY

The United States considers the Global Positioning System (GPS), a satellite radio navigation system, to be vital to its national and homeland security. America's military and critical infrastructures sectors rely on GPS for their operations.[1] The U.S. has made GPS extremely resistant to intentional and natural interference by placing its satellites in orbits beyond the reach of most anti-satellite weapons, flying significantly more satellites than required, and broadcasting multiple signals.[2] Despite these safeguards, the U.S. government has acknowledged the need to preserve and increase its GPS backups.[3] This begs the questions of: Why? And should more be done to address GPS's vulnerabilities?

The U.S. government faces several major challenges in determining if it has sufficient GPS backups. It does not strictly regulate, monitor, or keep statistics on how GPS is used.[4] It has terminated the operations of radio navigation systems that could have complemented or served as GPS backup.

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[1] White House, *NSPD-39: U.S. Space-Based Position, Navigation, and Timing Policy Fact Sheet* (Washington, DC: White House, 2004), http://fas.org/irp/offdocs/nspd/nspd-39.htm.

[2] Jaganath Sanakran, "Debating Space Security: Capabilities and Vulnerabilities" (PhD diss., University of Maryland, 2012), http://cissmdev.devcloud.acquia-sites.com/sites/default/files/papers/sankaran_debating_space_securitycapbilities_and_vulnerabilities.pdf, 78–92; Geoffrey Forden, "Viewpoint: China and Space War," *Astropolitics* 6, no. 2 (2008): 138–153; National Coordination Office for Space-Based Positioning, Navigation, and Timing, "The Global Positioning System," accessed July 13, 2015, http://www.gps.gov/systems/gps/; National Coordination Office for Space-Based Positioning, Navigation and Timing, "GPS Modernization," last modified April 26, 2016, http://www.gps.gov/systems/gps/modernization/; National Coordination Office for Space-Based Positioning, Navigation and Timing, "New Civil Signals," last modified August 12, 2016, http://www.gps.gov/systems/gps/modernization/civilsignals/.

[3] White House, *NSPD-39*; U.S. Department of Defense [DOD], U.S. Department of Homeland Security [DHS], and U.S. Department of Transportation [DOT], *2014 Federal Radio Navigation Plan* (Washington DC: National Technical Information Service, 2015), http://www.navcen.uscg.gov/pdf/FederalRadio NavigationPlan2014.pdf, 3–5.

[4] The U.S.' only restrictions on GPS are nation security related. In plain terms, GPS receivers or components with the following characteristics are subject to U.S. import and export laws: use military GPS signals, operate with anti-jamming antennas, operate on large drones, rockets, and missiles.

U.S.C., Title 22, ch. 1, subch. M, § 121.1, http://www.ecfr.gov/cgi-bin/text-idx?SID=86008bdffd1fb2e79cc5df41a180750a&node=22:1.0.1.13.58&rgn=div5.

Moreover, many U.S. industries and individual users do not have the infrastructures, backup devices, and processes to operate effectively and efficiently during a GPS outage.[5] Finally, the social science and policy analysis communities have not carried out sustained theory based research on GPS. Collectively, these factors limit the U.S.' ability to effectively identify and address all of GPS's vulnerabilities.

This thesis investigated why GPS's vulnerabilities have been an ongoing policy issue. It did so by examining how a shift in a conceptual lens from viewing GPS public utility to one of viewing it as a software platform changed our understanding of its criticality, resilience, and vulnerability. The public utility lens frames the role of GPS as a provider of critical navigation signals to its users while the software platform lens depicts the role of GPS as technology that serves a foundation or input on which new technologies and processes are built upon. Together, these two lenses describe GPS's full range of use.

Constant comparison analysis was used to examine GPS's roles as both a public utility and software platform. This application of constant comparison analysis assumed GPS salient characteristics reflect the goals and objectives of those who built, operate, and maintain it. Therefore, examination of the GPS system and the laws, polices, and practices that govern it operations can provide insights on its role as public utility and software platform. Furthermore, the constant comparison method does require quantitative data and a significant research literature. In other words, it allowed us to analyze GPS by using what is already known to about GPS and the policies that govern its operation.

The public utility lens revealed the U.S. uses system design and physical redundancies to increase GPS's resilience. It showed that every individual GPS satellite and ground facility contributes to the global production and transmission of navigation signals. This approach has increased GPS's resilience by reducing the criticality of every satellite and ground facility. Furthermore, it indicates the

[5] DOD, DHS, and DOT, *2014 Federal Radio Navigation Plan*, 5-4–5-8.

U.S. has further reduced criticality of these infrastructures by adding more satellites and ground facilities than what is required to meet minimum system performance requirements. Together, system design and redundancies have reduced GPS's vulnerability to major service interruptions.

The software platforms lens indicated the U.S. has further increased GPS resilience by treating it like an open source computer operating system instead of a software platform. Specifically, the U.S. does not actively manage the relationships between GPS satellite system, the technologies and process that complement it, and the interfaces controlling the relationships between these two platform elements. Rather, it has focused its efforts on improving the GPS resilience by maintaining existing signals while as the same time adding new ones to GPS operations. This has three major benefits. One, it has allowed GPS to continue providing its signal to existing GPS receivers. Two, it has provided GPS manufactures and applications developers with the opportunity to create more reliable, accurate, and resilient receivers and processes that use old and new GPS signals in their operations. However, there is no guarantee they will pursue this opportunity. Three, the additional new signals transform the existing GPS system into the functional equivalent of multiple satellite systems.

There are two major limitations of this thesis and the ongoing GPS policy discussions on GPS vulnerabilities. One, the lack of sustained theory based policy research on GPS has limited the development of overarching frameworks that can be used evaluate how political, economic, and social factors have influenced its technological development. Future GPS policy research based on the social construction of technology theory could provide us with concepts and methodologies to begin overcoming this analytical challenge. Two, a lack of statistical data on the number and types of GPS in operation has limited our ability to develop estimate how vulnerable GPS users actually are to service interruptions. Long-term data collections efforts, such as periodic market research and surveys, could provide use with the data necessary to develop models and metrics to analyze how America's GPS use and vulnerabilities are changing over time. The knowledge gained from these efforts can help inform the public debate on GPS's vulnerabilities and future policy decisions that will be required to address them.

ACKNOWLEDGMENTS

The late Nelson Mandela once said: “In Africa, there is a concept known as ‘ubuntu’—the profound sense that we are human only through the humanity of others; that if we are to accomplish anything in this world, it in will equal measure be due to the work and achievement of others.”

In the spirit of Mandela’s quote, I would like to acknowledge the contributions of those whose efforts have helped me become a more confident scholar and PhD practitioner and have allowed me to complete this thesis. I am thankful for the sacrifices made by wife, kids, and my U.S. Coast Guard colleagues (particularly LCDR Sarah Rousseau and LCDR Stacia Parrott). I am grateful for Dr. Rodrigo Nieto-Gómez, my thesis advisor, for his patience and encouragement! I am indebted to Dr. Lauren Wollman, my research coach, for her tireless efforts in pushing me to master research fundamentals and do my best work possible given the time constraints! I am extremely appreciative of Dr. Christopher Bellavita’s attention to detail in providing CHDS students a vast array of tools necessary to overcome the inevitable stresses of completing a master’s thesis as an adult student in an intense distance-learning program. I would also like to thank my friends Lou DiDominicus and Karl Davis for being my thesis cheerleaders. Finally, I would like to thank my CHDS classmates who opened my eyes to the broad range of homeland security challenges that our nation’s civil servants face every day.

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# I. INTRODUCTION

## A. PROBLEM STATEMENT

The United States (U.S.) considers the Global Positioning System (GPS), a satellite radio navigation system, to be vital to its national and homeland security.[1] America's military and critical infrastructures sectors rely on GPS for their operations. The U.S. has made GPS extremely resistant to intentional and natural interference by placing its satellites in orbits beyond the reach of most anti-satellite weapons, flying significantly more satellites than required, and broadcasting multiple signals.[2] Theoretically, major wars with space combat, targeted attacks against critical sub-systems, or extreme space weather are the only major occurrences that could interrupt GPS's operation for an extended period of time. Despite these safeguards, the U.S. government has acknowledged the need to preserve and increase its GPS backups.[3] This begs the questions of: Why? And should more be done to address GPS's vulnerabilities?

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[1] White House, *NSPD-39: U.S. Space-Based Position, Navigation, and Timing Policy Fact Sheet* (Washington, DC: White House, 2004), http://fas.org/irp/offdocs/nspd/nspd-39.htm.

[2] Jaganath Sanakran, "Debating Space Security: Capabilities and Vulnerabilities" (PhD diss., University of Maryland, 2012), http://cissmdev.devcloud.acquia-sites.com/sites/default/files/papers/sankaran_debating_space_securitycapbilities_and_vulnerabilities.pdf, 78–92; Geoffrey Forden, "Viewpoint: China and Space War," *Astropolitics* 6, no. 2 (2008): 138–153; National Coordination Office for Space-Based Positioning, Navigation, and Timing [National Coordination Office], "The Global Positioning System," last modified February 11, 2014, http://www.gps.gov/systems/gps/; National Coordination Office for Space-Based Positioning, Navigation and Timing [National Coordination Office], "GPS Modernization," last modified April 26, 2016, http://www.gps.gov/systems/gps/modernization/; National Coordination Office for Space-Based Positioning, Navigation and Timing, "New Civil Signals," last modified August 12, 2016, http://www.gps.gov/systems/gps/modernization/civilsignals/.

[3] White House, *NSPD-39*; White House, *National Space Policy of United States* (Washington DC: White House, 2010), https://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf, 5; U.S. Department of Defense [DOD], U.S. Department of Homeland Security [DHS], and U.S. Department of Transportation [DOT], *2014 Federal Radio Navigation Plan* (Washington DC: National Technical Information Service, 2015), http://www.navcen.uscg.gov/pdf/FederalRadioNavigationPlan2014.pdf, 3-5.

Current U.S. government policy contends existing industry backup systems and procedures are sufficient to address a GPS disruption.[4] The U.S. National Space-Based Positioning, Navigation, and Timing Advisory Board, research organizations, and non-profit institutions have quietly argued this may not be the case.[5] To save money, the U.S. government has terminated the operation of federally funded navigation systems that could complement or backup the GPS system. Localized GPS disruptions, such as the U.S. Navy's accidental jamming of GPS signal in San Diego, California and the use of personal GPS jamming devices in the vicinity of New Jersey's Newark International Airport, have caused failures in air traffic control, communications, maritime security, and navigation systems.[6] These failures clearly call into question the adequacy of existing GPS backups. There are concerns the U.S. is becoming increasingly overly reliant on GPS, existing GPS backups may not be adequate, and the associated risks of a GPS disruption are not acceptable.

To complicate matters further, there is wide variation in how different industries use and backup GPS. Some industries, such as commercial aviation and marine shipping, have supporting infrastructures, backup devices, and processes allowing them to continuing operating during a GPS outage.[7] However, there are many economic sectors that do not have these safeguards in place. Some industries, such as commercial surveying, precision farming, and oil

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4 "Record of Decision (ROD) on the U.S. Coast Guard Long Range Aids to Navigation (Loran-C) Program," *Federal Register* 75, no. 4 (January 7, 2010): 997–998; "Terminate Long Range Aids to Navigation (Loran-C) Signal (Notice)," *Federal Register* 5, no. 4 (January 7, 2010): 998.

5 Bradford Parkinson et al., *Independent Assessment Team (IAT) Summary of Initial Findings on eLoran* (Alexandria, VA: Institute for Defense Analysis, 2009); National Space-Based Positioning, Navigation, and Timing Advisory Board [PNT], *Jamming the Global Positioning System—A National Security Threat: Recent Events and Potential Cures* (Washington, DC: National Space-Based Positioning, Navigation, and Timing Advisory Board, 2010); Royal Academy of Engineering, *Global Navigation Space Systems: Reliance and Vulnerabilities* (London, UK: Royal Academy of Engineering, 2011); Resilient Navigation and Timing Foundation, "What We Do," 2015, http://rntfnd.org/what-we-do/.

6 Parkinson et al., *Independent Assessment Team*, A2–A3; PNT, *Jamming the Global Positioning System*, 4–5.

7 DOD, DHS, and DOT, *2014 Federal Radio Navigation Plan*, 5-4–5-8.

drilling, most likely will lose the GPS related efficiency and safety benefits during a service disruption.[8] Finally, some industries and firms, such as those providing on demand transportation services and vehicle tracking, may simply cease operations because their business processes are based on GPS's constant availability and they do not have backups.[9]

Furthermore, America does not truly know the full extent of GPS's use and its associated vulnerabilities, nor does it strictly regulate, monitor, or keep statistics on how GPS is used.[10] Instead, it has encouraged GPS's adoption of freely sharing civil GPS civil specifications and signals.[11] Manufacturers and software developers are free to develop civil GPS related products and services. Firms and individuals are free to determine how they will incorporate GPS into their products, processes, and daily activities. GPS, as a result of these polices, has expanded beyond navigation to include virtually every economic sector and activity using information technology. Unfortunately, the U.S. cannot effectively address GPS's vulnerabilities without taking into account the scope and scale of its use.

Finally, the social science and policy research communities have not made GPS a focus of sustained theory based research. The majority of policy research establishing America's GPS policy was conducted between 1970 and 1995. Since then, the publicly available policy literature has narrowly focused on describing GPS's importance to the public and/or analyzing individual GPS policy decisions and their outcomes. The GPS policy literature does not systematically

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[8] Ibid., 5-8.

[9] Ibid.

[10] The U.S.' only restrictions on GPS are nation security related. In plain terms, GPS receivers or components with the following characteristics are subject to U.S. import and export laws: use military GPS signals, operate with anti-jamming antennas, operate on large drones, rockets and missiles. U.S.C. Title 22, ch. 1, subch. M, § 121.1, http://www.ecfr.gov/cgi-bin/text-idx?SID=86008bdffd1fb2e79cc5df41a180750a&node=22:1.0.1.13.58&rgn=div5.

[11] National Coordination Office for Space-Based Positioning, Navigation and Timing, "Technical Documentation," last modified July 1, 2016, http://www.gps.gov/technical/.

10 U.S.C. § 2281, http://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title10-section2281&num=0&edition=prelim.

account for the myriad of political, economic, sociological, and technological changes that have occurred since 1995. As a result, there is not one overarching theoretical or conceptual framework that accounts for the myriad of roles GPS plays in today's world. These shortcomings limit the U.S. government's ability to effectively address GPS's vulnerabilities.

## B. RESEARCH QUESTION

This thesis seeks to gain a better understanding of why GPS's vulnerabilities have been an enduring U.S. public policy concern. It does so by answering the following research question: How does a shift in conceptual lenses from viewing GPS as a public utility to that of a software platform change our understanding of its criticality, resilience, and vulnerability?

Together, these conceptual lenses provide two perspectives to describe GPS's full range of uses. The public utility lens focuses on how GPS delivers its signals to its users. Conversely, the software platform conceptual lens examines how nations, organizations, and individuals use GPS as a technological foundation for products and services. Moreover, the use of this conceptual lens allows us to address this thesis's two major research challenges: lack of statistical data and limited policy literature.

## *C.* RESEARCH METHODOLOGY

A constant comparison research methodology will be used to examine GPS's role as public utility and a software platform. This research

> strategy involves taking one piece of data (one interview, one statement, one theme) and comparing it to all others that may be similar or different in order to develop conceptualizations of the possible relations between the various pieces of data.[12]

It is a useful approach for conducting research on human phenomena for which there is limited research and data. It assumes "fundamental social processes

[12] Sally Thorne, "Data Analysis in Qualitative Research," *Evidence-Based Nursing* 3, no. 3 (2000): 69.

explain something about human behavior and experience."[13] In plain terms, it asserts that knowledge, insights, and theory about a social outcome can be developed by observing and analyzing the human systems and activities that produce them.

### 1. Research Significance

By extension, the constant comparison method can provide new knowledge on the nature of GPS's criticality, resilience, and vulnerabilities. GPS's salient characteristics, like those of all man-made systems, are a reflection of the goals and objectives of those who have and operate it. Therefore, constant comparison analysis can potentially provide us new GPS insights by examining the relationships between how the GPS system functions and the policies and rules governing its operations. Specifically, by evaluating GPS's roles as a public utility and a software platform, it can provide us with a more holistic view of these relationships.

### 2. GPS as a Public Utility

The public utility lens focuses on GPS's role as a government regulated enterprise that operates and maintains a physical infrastructure for the purpose of producing and delivering an essential good or service to its customers.[14] A public utility is often the sole provider of a vital good or service for its customers. Therefore, it is critical that a public utility provide its users with extremely reliable service. The failure or degradation in a public utility's performance will most likely have significant negative impacts on the organizations and individuals who directly and indirectly rely on it.

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13 Ibid.

14 James C. Bonbright, *Principles of Public Utility Rates* (New York: Columbia University Press, 1961), http://media.terry.uga.edu/documents/exec_ed/bonbright/principles_of_public_utility_rates.pdf, 3; John Black, ed., *Oxford Dictionary of Economics* (New York: Oxford University Press, 1997), 380; Rick Geddes, "Public Utilities," in *The Encyclopedia of Law and Economic*, ed. Boudewijn Bouchaert and Gerrit De Gest, 1163–1164 (Cheltenham, UK: Edward Elgar, 2000), http://www.human.cornell.edu/pam/cpip/upload/RRg-bookchapter-Public-Utilities.pdf.

The U.S. has characterized GPS as a global information utility that provides signals to GPS users throughout the world.[15] Many nations rely on GPS for the operations of their military and their civilian infrastructures. A failure of degradation in GPS's performance could have significant and widespread international and domestic impacts. Specifically, it could undermine U.S. and allied military operations, trigger economic losses, and lead to accidents, deaths, and property damages that otherwise would not occur.

America, like a public utility operator, has taken significant steps to prevent and mitigate the consequences of a service disruption. It has in orbit at least 31 active and reserve GPS satellites—30 percent more satellites than the 24 required for global coverage.[16] The U.S. has increased the number of civil and military GPS signals, reducing the potential that atmospheric condition, extreme space weather, and intentional interference (jamming and false broadcasts) could degrade GPS's accuracy and reliability.[17] Finally, it operates and maintains a globally dispersed infrastructure to monitor and correct GPS's operational performance.[18]

### 3. GPS as a Software Platform

The software platform conceptual lens recognizes that GPS's uses have moved far beyond positioning, navigation, and timing. A software platform is a technology that uses written language or code to create value by providing services to multiple and distinct groups of application developers, hardware

15 White House, *NSPD-39*.

16 National Coordination Office for Space-Based Positioning, Navigation and Timing [National Coordination Office], "Space Segment," last modified March 9, 2016, http://www.gps.gov/systems/gps/control/#modernization.

17 National Coordination Office, "GPS Modernization."

18 National Coordination Office for Space-Based Positioning, Navigation and Timing [National Coordination Office], "Control Segment," last modified April 13, 2016, http://www.gps.gov/systems/gps/control/#modernization.

manufacturers, and users.[19] They are able to do this because once their codes are developed, they can at very little cost and effort and easily be reused and/or modified to operate with other technologies and processes.[20] As a result, they can become “a base upon which other applications, processes or technologies are developed.”[21]

In its desire to promote GPS’s adoption and continued use, the United States has implemented a range of policies and laws that have in effect transformed GPS from a navigation system to a software platform. It continuously and globally broadcasts GPS signals from space to Earth free of charge,[22] And anyone who has a GPS receiver can utilize the GPS signal. It has made many of GPS civil specifications publicly available.[23] Manufacturers and application developers can use them to create new products and services without paying for GPS’s technical specifications and signals. Finally, to keep GPS as the world’s premier global satellite navigation system,[24] America has added more satellite and signals to the GPS system.[25]

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19 David S. Evans, Andrei Hagiu, and Richard Schmalensee, *Invisible Engines: How Software Platforms Drive Innovation and Transform Industries* (Cambridge MA: MIT Press, 2008), Kindle edition, Kindle locations 78–97.

20 Ibid., Kindle location 115.

21 *Technopedia*, s.v. “Platform,” accessed February 14, 2016, https://www.techopedia.com/definition/3411/platform.

22 National Coordination Office for Space-Based Positioning, Navigation and Timing [National Coordination Office], “United States Policy,” last modified July 1, 2016, http://www.gps.gov/policy/.

23 National Coordination Office, “Technical Documentation.”

24 European Space Agency, “Galileo Future and Evolutions,” last modified April 24 2013, *Navipedia*, accessed September 12, 2016, http://www.navipedia.org/index.php/Galileo_Future_and_Evolutions. There are currently two fully operational global satellite navigation systems: the U.S. GPS system and Russia’s GLONASS. The European Union is currently developing its Galileo satellite navigation system, which is scheduled to be completed in 2020.

China is also developing its Beidou2 satellite navigation system, which is also scheduled to become fully operational in 2020. European Space Agency, “BeiDou Future and Evolutions,” last modified August 5 2016, *Navipedia*, accessed September 12, 2016, http://www.navipedia.org/index.php/BeiDou_Future_and_Evolutions.

25 National Coordination Office, “United States Policy.”

The collective result of these policies is that the U.S. government has become the GPS software platform owner or keystone firm for many of the world's industries and companies. A platform owner/keystone firm is the one that controls how applications operate and interface with the main software.[26] In this role, the U.S. provides the GPS core functionality, which is the provision of civil and military signals. These signals are used for positioning, navigation, and timing. It also controls GPS technical specifications and system operations, which determine how manufacturers, application developers, and users incorporate GPS in their products, services and activities.

Furthermore, as a result of American policies, GPS has become a keystone firm in many well established industries, corporations, and their associated technologies and processes. For instance, the U.S. military uses GPS in its navigation, logistics, communications, intelligence, and weapons systems. Major communication providers (e.g., AT&T and Verizon) and public utilities (e.g., electricity companies) use GPS's timing signals to help manage and route the flow of transmission through their respective systems. Software developers (e.g., Apple, Google and Waze) use GPS to facilitate the development of new applications to make their products and services more attractive to existing and potential customers. GPS's widespread use means that many economic sectors and activities could be negatively impacted should an outage occur.

## D. SELECTION

There are two major factors that determine the scale, scope, and nature of GPS's criticality, resilience, and vulnerabilities. The first is simply the law of physics. GPS operates by broadcasting low-powered signals that are extremely susceptible to disruption from atmospheric conditions, electronic jamming, and

[26] Amrit Tiwana, *Platform Ecosystem Aligning Architecture, Governance, and Strategy* (Waltham, MA: Elsevier, 2014), 5.

false broadcasts.[27] The second factor is how the U.S. has designed, operated, and managed GPS. Each of these factors has different research implications.

By themselves, GPS's low-powered signals provide limited explanation for why GPS's vulnerabilities have been an ongoing U.S. policy issue. The laws of nature governing how GPS operates are constant. In other words, GPS's low signal power has and will continue to be a source of GPS vulnerabilities. Although important, it provides limited insight as to why GPS vulnerabilities have been a long-term policy issue.

GPS's design, operation, and management may have strong explanatory power on why its vulnerabilities have been a persistent public policy concern. These system characteristics are a reflection of the goals and objectives America hopes to achieve by providing GPS globally and free of charge. Through GPS's design and operations, the United States has determined who can use the system and how it is used. There have been changes in these parameters over the course of GPS's history. Each of these changes may have increased, decreased, or had no impact on the scale, scope, and the potential consequences of GPS's vulnerabilities. Examining these changes through a public utility and software platform lens may provide us with broader and deeper insights on GPS's criticality, resilience, and vulnerabilities.

### 1. Data

The primary sources of data for this analysis will be GPS's policies, its operational systems, and its existing policy literature. The U.S.' policy goals, laws, regulations, and practices determine who uses GPS and how they use it. America's design, operations, and management of GPS systems not only reflect these factors but also exert a strong influence on GPS's criticality, resilience, and vulnerabilities. Finally, the existing GPS policy literature, which consists of presidential directives, U.S. laws and research reports, provides the background,

[27] PNT, *Jamming the Global Positioning System*, 3–6; Mark Goldstein and Joseph Kirschbaum, *GPS Disruptions: Efforts to Assess Risks to Critical Infrastructure and Coordinate Agency Actions Should Be Enhanced* (Washington DC: General Accountability Office, 2013), 10.

rationale, and an analysis necessary to understand how GPS has evolved over time. Together, these three different data sources can provide the information to evaluate GPS from the perspectives of it being a public utility and a software platform.

### 2. Outputs

The primary output of this research is the analysis of GPS as a public utility and as a software platform. Together, these two lenses may provide insights about GPS's criticality, resilience, and vulnerability that might not otherwise be recognized. Furthermore, each lens can extend the public utility and software platform research literatures to study GPS. This in turn can contribute to the development of conceptual frameworks that can be used to evaluate GPS and inform policy decision. Moreover, these two lenses can provide the insights required to make real-world GPS decisions, while at the same time using the discipline of scientific method to more fully understand GPS. Finally, it will help decision makers, analysts, scientists, and scholars to directly tie basic research back to GPS policy.

# II. LITERATURE REVIEW

This chapter reviews and assesses the existing GPS literature to better understand why GPS's vulnerabilities have been a persistent U.S. national and homeland security issue. The social science and policy research communities have not made GPS a focus of sustained theory based research. As a result, there is not a GPS specific theoretical or conceptual framework to evaluate GPS and its vulnerabilities.

## A. THEMES IN LITERATURE ABOUT GPS'S ROLES

Despite this limitation, there are three broad themes within the reviewed literature that can be used to help structure policy analysis on GPS's vulnerabilities. Each theme assumes GPS serves national goals beyond its primary purpose of providing its users with a signal. The first theme considers GPS as a tool the U.S. has used to reduce the cost of operating and maintaining its federal radio navigation system. The second theme asserts GPS has become an element of America's foreign, national security, and economic policies. The third theme warns that from the perspectives of some in the military, transportation, and scientific communities, GPS is more vulnerable than commonly believed. These themes individually and collectively provide insight on why GPS vulnerabilities have been an enduring U.S. public policy concern.

### 1. GPS is a Management Tool

The U.S. government has historically treated GPS as a management tool it could use to reduce the number of federal navigation systems and their total budgetary costs. This trend manifested itself in 1973 when the Department of Defense (DOD) created the GPS program by merging two satellite development programs.[28] Cost was a major reason for this consolidation. DOD did not believe

[28] Bradford Parkinson and Stephen Gilbert, "NAVSTAR: Global Positioning System-Ten Years Later," *Proceedings of the IEEE* 71, no. 10 (1983): 1177.

it could afford to "develop, deploy, and operate" two separate systems serving a common navigational purpose.[29]

GPS's creation is indicative of a larger trend to minimize federal radio navigation costs through consolidation. The U.S. president, Congress, and General Accounting Office (GAO) expressed a desire to reduce the cost of its federal radio navigation budget. GAO noted in a 1974 report that individuals in government and industry were concerned there was a "proliferation of federal radio navigation systems whose mounting costs must be borne by Government and users alike."[30] Therefore, GAO called for a "national plan for navigation" to achieve the minimum of navigation systems to meet long-range military and civil air, land, and sea navigation requirements.[31]

In a 1978 report, the GAO again expressed concern about the number and cost of federal radio navigation systems. It concluded there was a "proliferation of overlapping navigation systems with significantly higher cost to the Government and users."[32] Therefore, GAO called for a government-wide plan to address this concern.[33] Furthermore, GAO recommended the president appoint a manager who had the authority and budgetary control to implement this navigation plan. Finally, GAO suggested the GPS system, which was under development at the time, take into account civil (non-military) requirements and be used to reduce the number of federally provided navigation systems.[34] Congress responded to this report by including in the International Maritime Satellite Communications Act of 1978 a requirement the president produce a

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[29] Ibid.

[30] Elmer Staats, *Report to the Subcommittee on Coast Guard and Navigation Committee on Merchant Marine and Fisheries United States House of Representatives. Summary of GAO Study of Radio Navigation Systems: Meeting Maritime Needs* (Washington DC: U.S General Accounting Office, 1974), 1, 5.

[31] Ibid., 7.

[32] Elmer Staats, *Navigation Planning: Need for a New Direction* (Washington DC: U.S. General Accounting Office, 1978), i.

[33] Ibid.

[34] Ibid., i–ii.

plan to reduce the number and redundancy of federal radio navigation systems.[35]

Since 1980, the U.S. Departments of Defense, and Transportation (DOT) have been jointly responsible for meeting Congress's requirement for a government navigation plan; the Department of Homeland Security was also given this responsibility in 2002.[36] This plan is known as the *U.S. Federal Radio Navigation Plan* and has generally speaking been published every two years. These plans have since 1980 have called for the for the minimum number of federal navigation systems required to meet air, land, and marine navigation requirements.[37] They have used GPS to make this objective a reality. They have consistently called for GPS to replace federal radio navigation systems that are no longer cost-effective. Over the course of approximately 30 years, the U.S. has decommissioned all of its other satellite and terrestrial radio navigation systems. In their place, it has created a system of systems that use GPS to meet the positioning, navigation, and timing requirements of virtually all of the U.S. air, land, and marine federal radio navigation system users.

The literature characterizing GPS as a management tool has several major shortcomings. For instance, it assumes multiple and overlapping federal radio navigation systems are redundant and not cost-effective. This assumption may no longer hold true now given that the world has changed dramatically since the first U.S. *Radio Navigation Plan* was published in 1980. Specifically, GPS's use has expanded far beyond navigation to include many more uses such as telecommunications, logistics, and information technology. U.S. *Federal Radio Navigation Plans* recognize this changes and indicate there are opportunity costs, and trade-offs in making radio navigation policy decisions. They outline an

35 International Maritime Satellite Telecommunications Act, Pub L. No. 95-564, Stat. 2394 (1978), https://www.gpo.gov/fdsys/pkg/STATUTE-92/pdf/STATUTE-92-Pg2392.pdf.

36 The Department of the Homeland Security became a signatory to the U.S. *Federal Radio Navigation Plan* with the passage of Homeland Security Act of 2002. The 2005 *Federal Radio Navigation Plan* was the first one to include the DHS as a signatory.

37 This is based on my reading of the U.S. *Federal Radio Navigation Plans* and my understanding of the literature.

analytical process to address them; however, there does not appear to be any public reports verifying how these trade-off analyses occurred. Finally, this body of literature does not take into account how GPS may have eroded the systems and processes needed to operate without it.

### 2. GPS is an Element of American Foreign Policy, National Defense, and Economic Policy

The U.S. in addition to using GPS as a management tool has made it an element of its foreign policy, national defense, and economic policies. America has consistently and publicly affirmed that the world would benefit through the shared use of GPS. President Reagan is credited with starting this trend, when, in response to the Soviet Union's shooting down of a lost Korean Airliner in 1983, he formally declared the U.S. would make GPS available for civilian use.[38]

Ten years later, the U.S. government began commissioning a series of policy studies to determine how it should govern the GPS a dual-use system—one that can be used for military and civilian purposes. The 1993 Joint DOD/DOT Task Force on GPS conducted a policy analysis to determine how to best govern GPS as a dual-use system. Its recommendations were that DOD and DOT should jointly manage the GPS system.[39] In 1995, the National Academy of Public Administration (NAPA) and National Research Council (NRC) suggested the governance of GPS should be expanded beyond DOD and DOT to include the Departments of State, Commerce, and the Interior.[40] Also in 1995, RAND provided some support for these recommendations by recommending the U.S.

[38] "Statement by Deputy Press Secretary Speakes on the Soviet Attack on a Korean Civilian Airliner," American Presidency Project, September 16, 1983, http://www.presidency.ucsb.edu/ws/?pid=41856.

[39] Joint DOD/DOT Task Force, *The Global Positioning System Management and Operation of a Dual Use System: A Report to the Secretaries of Defense and Transportation* (Washington DC: U.S. Departments of Defense and Transportation, 1993), ES2–ES3.

[40] National Academy of Public Administration [NAPA] and National Research Council [NRC], *The Global Positioning System: Charting the Future Summary Report* (Washington DC: National Academy of Public Administration, 1995), ix.

maintain control over the GPS system while allowing either public or private organizations to operate GPS augmentations.[41]

During the studies, the U.S. government reexamined the issue of how GPS should be funded. Up to that time, America had been providing its GPS signals free of charge. The 1993 Joint/DOD Task Force recommended the U.S. government continue to provide the service of GPS and its augmentations without charging users.[42] In 1995, NAPA/NRC concluded this funding arrangement was "remarkably sound" and should be kept in place.[43] Additionally, it asserted there was no need for major change.[44] Moreover, it noted that the U.S. has and would continue to receive economic and strategic benefit by providing GPS free of charge. Specifically, GPS would become the world's de facto satellite radio navigation system and would stimulate U.S. and international economic growth and innovation.[45] RAND agreed with this assessment, stating that the U.S.' "no fee approach" had stimulated GPS adoption and economic growth. RAND also noted would be "difficult or impossible" to collect user fees.[46]

The U.S. government's GPS studies examined the issues of adversaries using GPS and its augmentations against America and its allies. The 1993 Joint DOD/DOT Task force argued that the U.S. should provide ground and satellite based GPS augmentations but expressed concern these systems undermine selective availability (SA)—a GPS design feature that allows the U.S. to intentionally degrade the GPS's civil signal in order to prevent enemy use.[47] In their 1995 report, NAPA and NRC, all acknowledged these concerns but pointed out that an enemy sophisticated enough to use guided weapons could find ways

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41 Scott Pace et al., *The Global Positioning System Assessing National Policies* (Santa Monica, CA: RAND, 1995), xxvi–xxvii.

42 Joint DOD/DOT Task Force, *The Global Positioning System*, ES–3.

43 NAPA and NRC, *The Global Positioning System*, viii.

44 Ibid.

45 Ibid., 6–12.

46 Pace et al., *The Global Positioning System*, xxi.

47 Joint DOD/DOT Task Force, *The Global Positioning System*, 33.

to circumvent SA.[48]Furthermore, reports from the DOD/DOT Task Force noted foreign governments were suspicious of SA, making them hesitant to fully adopt GPS.[49] Therefore, all of these studies recommend the U.S. consider courses of actions, such as presidential directives, treaties and legislation, to alleviate these concerns.

The U.S. government since GPS became fully operational has implemented the majority of the recommendations made in these studies. Presidents Clinton, Bush, and Obama have published national policies affirming the U.S.' commitment to promoting the free and peaceful use of GPS's civil signals.[50] These stated the U.S. would work with other nations to facilitate the use of GPS for scientific and transportation purposes. In addition, they directed the use of national level committees and boards to advise and coordinate the federal government's GPS related efforts. In addition, the U.S. government has also established federally operated GPS augmentation—systems that further increase GPS's accuracy and make it suitable for activities such as commercial aviation, which require precise navigation.[51]

Congress has also supported these presidential directives by enacting supporting legislation and authorizing GPS acquisitions. U.S. Code Title 10, § 2281 requires DOD to provide the civil GPS signal globally free of charge.[52] It also directs DOD to develop the capabilities to prevent enemy use of GPS without disrupting service for its peaceful use. In addition, the Strom Thurmond National Defense Authorization Act for Fiscal Year 1999 authorizes the DOD to

48 NAPA and NRC, *The Global Positioning System*, 24; Pace et al., *The Global Positioning System*, 90.

49 Joint DOD/DOT Task Force, *The Global Positioning System*, 45.

50 White House, *NSPD-39*; Office of Science and Technology, National Security Council, "Fact Sheet Global Positioning System," press release, March 29, 1996, http://clinton2.nara.gov/WH/EOP/OSTP/html/gps-factsheet.html.

51 DOD, DHS, and DOT, *2014 Federal Radio Navigation Plan*, 5-9, 5-10.

52 National Coordination Office for Space-Based Positioning, Navigation and Timing, "United States Code," last modified February 5, 2016, http://www.gps.gov/policy/legislation/uscode/#title10.

modernize GPS by building satellites capable of broadcasting multiple civil and military signals.[53] Furthermore, Title 51 of the U.S. Code, § 50112 urges the free global provision of GPS and the "promotion of GPS as an international standard."[54] Finally, the John Warner National Defense Authorization Act for Fiscal Year 2007 authorizes funding for the "National Space-Based Positioning, Navigation, and Timing Executive Committee and related organizations" for purpose of providing national oversight of America's GPS efforts.[55]

Generally speaking, the literature directly asserts or implies that these presidential directives and supporting legislation are the source of GPS's success as technology but notes they may also be a source of vulnerability. One author, Lachow asserts GPS provides significant economic and military benefits, but it also provides enemies with an opportunity to attack the U.S.[56] He asserts the U.S. risks losing GPS's benefits if it restricts civilian access to GPS and its augmentations. Writing in 2002, McNeff contends that due to U.S. government policies, GPS has become a very successful technology, and he argues the biggest risk to GPS is its management.[57] The U.S. has to manage and adapt the system for the future military and economic environment. Johnson and Warner state that GPS has become extremely important to the U.S. economy; however, they warn GPS's civil signals are vulnerable to attack as their signals are "unencrypted and unauthenticated."[58] Hoey and Benshoof provide similar findings, noting GPS has become extremely important to the U.S. military and

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[53] Ibid.

[54] Ibid.

[55] Ibid.

[56] Irving Lachow, "The GPS Dilemma: Balancing Military Risks and Economic Benefits," *International Security* 20, no. 1 (1995): 126–148.

[57] Jules McNeff, "The Global Positioning System," *IEEE Transaction on Microwave Theory and Techniques* 50, no. 3 (2002): 645–652.

[58] Roger Johnson and Joo Warner, "Think GPS Offers High Security? Think Again" (presented at Business Contingency Planning Conference, Las Vegas, NV: Los Alamos Labs, 2004), http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-04-1692.

economy.[59] Their warning is also similar to that of Johnson and Warner, as they note the GPS's civil signal is vulnerable to disruption and warn that the U.S. is becoming too reliant on GPS.

### 3. GPS is Vulnerable

The U.S. has designed and modified the GPS system to be extremely resistant to man-made and natural disruptions. It has employed a variety of means, such as extra satellites, new signals, constant monitoring, and international partnerships, to achieve this outcome. Current U.S. policy as collectively expressed in the president's 2010 budget, the 2010 Department of Homeland Security Appropriations Act, and the "Record of Decision on the U.S. Coast Guard's Long Range Navigation (LORAN-C) Program" assumes existing backups are sufficient to prevent and mitigate GPS disruptions.[60] However, there is a small body of the policy literature consisting of works from the military, transportation, and scientific fields challenging this assertion.

#### *a. Military Literature*

American military policy literature, such as McPherson, Revoir, Cluff, and Wilgenbusch and Heisig, have voiced concerns that GPS has become a critical vulnerability.[61] GPS has transformed how American and allied forces are

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[59] David Hoey and Paul Benshoof, *Civil GPS Systems and Potential Vulnerabilitie*s (Eglin AFB, FL: 46th Test Group, 2005), http://www.dtic.mil/dtic/tr/fulltext/u2/a440379.pdf.

[60] "Record of Decision (ROD) on the U.S. Coast Guard," 997; "Terminate Long Range Aids," 998; Department of Homeland Security Appropriations Act of 2010, Pub. L. No. 111-83 (2009); U.S. Office of Management and Budget, *Terminations, Reductions, and Savings Budget of the U.S. Government Fiscal Year 2010* (Washington DC: U.S. Office of Management and Budget, 2009), https://www.gpo.gov/fdsys/search/pagedetails.action?collectionCode=BUDGET&granuleId=&packageId=BUDGET-2010-TRS&fromBrowse=true.

[61] Michael McPherson, *GPS and the Joint Force Commander: Critical Asset, Critical Vulnerability* (Newport, RI: Naval War College, 2001); J. W. Rooker, *Satellite Vulnerabilities EWS Contemporary Issue Paper* (U.S. Marine Corps, Command and Staff College, 2008), http://www.dtic.mil/dtic/tr/fulltext/u2/a507952.pdf; James Cluff, *Where's My GPS? Ensuring Combat Capability in Degraded PNT Environment* (Maxwell Air Force Base, AL: Air University, 2011); Ronald Wilgenbusch and Alan Heisig, "Command and Control Vulnerabilities to Communications Jamming," *Joint Forces Quarterly* 69, no. 2 (2013): 56–63, http://ndupress.ndu.edu/Portals/68/Documents/jfq/jfq-69/JFQ-69_56-63_Wilgenbusch-Heisig.pdf.

organized, trained, and equipped. Specifically, GPS has enabled the development and operations of an extremely efficient, lethal and mobile military force that routinely uses a wide array of advanced technologies, such as drones, guided munitions, precision strike weapons, and satellite imagery. Enemy denial or degradation of GPS could reduce or eliminate the military advantages these technologies provide.

The reviewed U.S. military literature assumes GPS will be attacked during an armed conflict. There is broad agreement within this literature that these attacks will most likely include electronic jamming. Nation states and non-state actors can easily purchase or fabricate jammers. Cluff points out China, North Korea, Russia, and Taiwan are just some of the nations that manufacture and sell GPS jammers. He also reports that Iraq and North Korea have previously jammed GPS. Moreover, this literature acknowledges that nation states, such as China and Russia, have developed or are developing new aircraft, cruise missiles, and anti-satellite weapons that could be used to attack GPS satellites and ground infrastructure. However, there is disagreement as to whether or not the foreign nations will actually attack these targets. Successfully doing so is believed to be difficult, provide limited strategic benefit, and would dramatically escalate a conflict.

#### *b. Transportation Literature*

The U.S. DOT commissioned four major studies between 2001 and 2006 that recommended the U.S. develop a national backup to GPS. For example, John A. Volpe National Transportation Systems Center found that the U.S. transportation industry was extremely reliant on GPS and could experience difficulty in a severe GPS disruption.[62] It recommended the U.S. emphasize that transportation industry train for GPS loss, encourage use of GPS signal integrity monitors, develop in-vehicle GPS backups, and evaluate the range of radio

[62] John A. Volpe National Transportation Systems Center [Volpe], *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System* (Cambridge MA: John A. Volpe National Transportation Systems Center, 2001), ES3.

navigation systems necessary to backup GPS.[63] Another report by Volpe concluded that the benefits of using U.S. Coast Guard Long Range Navigation System (LORAN), a terrestrial radio navigation system, exceeded its cost if GPS experienced extended regional outages.[64] Narins concluded with some changes in equipment and signal modification that LORAN could serve as marine GPS backup and a limited aviation backup.[65] Parkinson et al. also favor LORAN as a back up to GPS. After they reviewed these and other relevant technical studies, they recommended that the U.S. government recapitalize LORAN to serve as a backup to GPS.[66] Based on these studies, DHS, with the concurrence of the Department of Homeland Security, announced via a press release that LORAN would serve as a national backup to GPS.[67] However, in a very unusual decision, the president and Congress rejected this consensus decision directing the Coast Guard to terminate the LORAN program.[68] They made this decision based on the determination that existing GPS backups were sufficient and that shutting down LORAN would save the taxpayer's money.[69]

The transportation literature examining the need for a GPS's backup has strengths and limitations, and it is primarily focused on the engineering and transportation concerns. For instance, Volpe provides an overview of GPS uses, vulnerabilities, and backups. It evaluates how GPS is used by function and

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63 Ibid., ES6.

64 John A. Volpe National Transportation Systems Center [Volpe], *Benefit-Cost Assessment of the Use of LORAN to Mitigate GPS Vulnerability for Positioning, Navigation, and Timing Services* (Cambridge MA: John A. Volpe National Transportation Systems Center, 2004).

65 Mitchell Narins, *Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications* (Washington DC: Federal Aviation Administration, 2004).

66 Parkinson et al., *Independent Assessment Team*.

67 U.S. Department of Homeland Security, "Statement from DHS Press Secretary Laura Keehhner on the Adoption of National Backup System to GPS," February 7, 2008, http://rntfnd.org/wp-content/uploads/DHS-Press-Release-GPS-Backup-2008.pdf.

68 Department of Homeland Security Appropriations Act of 2010; "Record of Decision (ROD) on the U.S. Coast Guard," 997; U.S. Office of Management and Budget, *Terminations, Reductions, and Savings*.

69 Ibid.

potential backups at different levels of transportation activity. It acknowledges but does not focus on the broader policy implications of the identified GPS vulnerabilities. Volpe considers GPS a supplement to existing navigation and timing technologies but underestimates its benefits. Furthermore, its report does not account for the opportunity costs (loss of life, inability to efficiently conduct operations) in the event of a GPS disruption.[70] The document by Narins, published by the Federal Aviation Administration, is primarily an engineering document and does not focus on surface transportation applications that may need a GPS backup.[71] It does not take this field of users into account as there are no specified requirements to the performance of GPS's land applications.[72] Though Parkinson et al. provide a summary of how LORAN can serve as backup to GPS and discuss some of the challenges, technical adoptions, and costs associated with making LORAN a GPS backup, they do not provide an in-depth discussion of the larger policy implications of not backing up GPS.[73] Finally, this body of literature assumes intentional interference will be the most likely cause of a GPS disruption.

#### *c. Scientific Literature*

In the 2000s, the U.S. government, scientific community, and private industry became increasingly concerned about the impacts of extreme space weather, conditions in space that affect the Earth and its technological systems, on GPS. The extreme space literature, such as works from National Science and Technology Council (NSATC), Ferguson et al., and Kiessling, have noted that society has become increasingly critically dependent on various critical infrastructures and systems, such as aircraft electrical grids, pipelines, and

[70] Volpe, *Benefit-Cost Assessment*.

[71] Narins, *Loran's Capability*.

[72] Ibid., 3-7.

[73] Parkinson et al., *Independent Assessment Team*.

satellites.[74] The literature points out atmospheric conditions on the sun can result in an abnormal amount of charged particles, electromagnetic energy, and plasma being radiated toward Earth. Depending on their severity, these solar emissions can cause a blackout of terrestrial and satellite radio broadcasts, disrupt electrical grids and pipelines, damage satellites and electronic equipment, and result in unsafe conditions for people (astronauts, pilots, and aircraft passengers) in the Earth's upper atmosphere.

The extreme space weather literature challenges the assertion that man-made interference is the most likely source of a major disruption. The National Oceanic and Atmospheric Administration's *Space Weather from the Sun* explains that the potential for extreme space weather always exists as the sun is continuously emitting charged particles and electromagnetic energy towards the Earth. It notes that the potential frequency and severity of space weather varies with where the sun is in its solar cycle—an 11-year period in which the number of sunspots goes from a minimum to a maximum and then returns to a minimum. It specifically asserts that the likelihood of extreme space increases as the solar maximum is approached.[75]

In addition, in 2013, the United Kingdom's Royal Academy of Engineering (RAE) estimated that every year there is up to a 12 percent chance of a Carrington event occurring.[76] This event is a type of extreme space weather consisting of a major coronal mass ejection that hurls an enormous amount of charged particles, electromagnetic energy, and plasma toward the Earth. The

[74] National Science and Technology Council, *National Space Weather Strategy* (Washington DC: Executive Office of the President of the United States, 2015); Dale Ferguson, Simon Worden, and Daniel Hastings, "The Space Weather Threat to Situational Awareness, Communications, and Positioning Systems," *IEEE Transaction On Plasma Science* 43, no. 9 (2015): 3086–3098; James Kiessling, "Robust Navigation Issue in the Event of GNSS Failures," 2013, http://www.cacr.caltech.edu/futureofutc/preprints/files/15_AAS%2013-508_Kiessling.pdf.

[75] Ferguson, Worden, and Hastings, "The Space Weather Threat."

[76] Royal Academy of Engineering, *Extreme Space Weather: Impacts on Engineered Systems and Infrastructure* (London, UK: Royal Academy of Engineering, 2013), http://www.raeng.org.uk/publications/reports/space-weather-full-report, 21.

RAE anticipates a Carrington event could disrupt GPS for up to three days and potentially damage or destroy some GPS satellites.[77]

The reviewed literature on extreme space weather has several limitations, which sources acknowledge in a very forthright manner. Overall, the sources making up the literature provide an overview and warnings of what are believed to be the most salient impacts of the different forms of extreme space weather; however, they do not include in-depth analyses or detailed estimates of the impacts of the space weather events. The NSATC recognizes space weather can pose an extreme threat event. Not only does it recommend the U.S. improve its understanding of space weather effects on critical infrastructure, it also recommends the U.S. enhance its capabilities to protect, mitigate, respond, and recover from extreme space weather.[78]

## B. SUMMARY OF THE THREE GPS LITERATURE THEMES

This review showed there are three themes within the GPS literature that can help frame research on GPS's vulnerabilities. America's use of GPS as a management tool has reduced the number of federal radio navigation systems, which has limited the U.S.' ability to operate during an interruption in GPS service. Moreover, the U.S.' treatment of GPS as an open technology has contributed to its widespread adoption. Finally, the U.S.' military, transportation and scientific communities have warned that because of these two factors GPS is far more vulnerable than believed.

The major shortcoming of these three themes is that they do not fully explain GPS's value proposition. Nor do they take into account how and why GPS provides benefits to those who directly and indirectly rely on it. The U.S. cannot effectively address GPS's vulnerabilities without taking these benefits into account.

[77] Ibid., 4–5.

[78] National Science and Technology Council, *National Space Weather Strategy*.

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# III. THE GPS SYSTEM

This chapter provides an overview of the two different sets of systems that make up GPS's operational infrastructure. First, it describes the GPS system, which consists of the satellites and ground infrastructure that produces and transmits GPS signals to users.[79] Then, it introduces and explains the specific roles America's five GPS augmentation systems, which improve the accuracy and reliability of GPS signals, allowing them to be use for activities with precise navigation requirements.[80] An understanding of how GPS and its augmentations work together is necessary to understand the nature of GPS's criticality, resilience, and vulnerability.

## A. THE GPS SYSTEM

The GPS system provides the basic signals that serve as the foundation for how GPS is used. It consists of three elements: space, control, and user. The U.S. government operates the space segment, which consists of GPS's satellites, and the control segment, which consists of GPS's ground infrastructure.[81] The GPS user segments consist of everyone who uses a GPS receiver.[82] Each of these segments plays a different role in GPS's operation.

### 1. Space Segment

The space segment has 31 operational satellites and several decommissioned satellites, which can be reactivated if needed.[83] These satellites fly above the Earth at altitude of 12,550 miles and are distributed

[79] 10 U.S.C. § 2281.

[80] White House, *NSPD-39*.

[81] U.S. Department of Defense [DOD], *Global Positioning System Standard Positioning Service Performance Standard*, 4th ed. (Washington DC: U.S. Department of Defense, 2008), http://www.gps.gov/technical/ps/2008-SPS-performance-standard.pdf, 1, 3.

[82] National Coordination Office, "The Global Positioning System."

[83] National Coordination Office, "Space Segment."

between six orbital planes.[84] Every GPS satellite in a 24-hour period will complete two orbits. This satellite constellation configuration provides the world with global GPS signal coverages. Most GPS users will receive signals from six satellites (only four are required to produce reliable navigation information.).[85]

There are currently three satellite generations in the operational GPS constellation. Each new generation of GPS satellites has new capabilities, making their signals more accurate, reliable, and resistant to interruption. Table 1 summarizes the salient characteristics of each of the three generations of operational GPS satellites.

Table 1. GPS's Operational Satellite Constellation[86]

| Characteristics | IIR | IIR(M) | IIF |
|---|---|---|---|
| Number | 12 | 7 | 12 |
| Design life | 7.5 | 7.5 | 7.5 |
| Launch years | 1997–2004 | 2005–2009 | 2010–2016 |
| Civil signals | 1 | 2 | 3 |
| Military signals | 2 | 2 | 2 |
| Military code | No | Yes | Yes |

Block IIR satellites are the oldest and least capable generation of GPS satellites. They account for 12 out of 31 operational GPS satellites (approximately 39 percent).[87] They entered service between 1997 and 2004 are beyond their 7.5-year design life,[88] and they broadcast only two signals. One of these signals is partially decrypted for civil GPS users,[89] and their second signal

[84] Ibid.

[85] U.S. Coast Guard Navigation Center, "General Information on GPS," February 1, 2016, http://www.navcen.uscg.gov/?pageName=GPSmain.

[86] Adapted from National Coordination Office, "Space Segment."

[87] Ibid.

[88] Ibid.

[89] Ibid.

is fully encrypted for military use.[90] They have the selective availability (SA) capability, which is a feature that allows the U.S. Air Force to degrade the civil GPS signal. SA reduces the ability of adversaries to use GPS to attack America and its allies.

The smallest generation of GPS satellites is the Block IIR (M) group. These satellites account for 23 percent of operational GPS satellites (seven out of 31).[91] They started operating between 2005 and 2009,[92] and they have all their surpassed their service life of 7.5 years.[93] Block IIR (M) satellites broadcast three sets of signals. They transmit two unencrypted civil signals and two encrypted military signals.[94] Additionally, they broadcast military code, which are encrypted signals to transmitted within a frequency range; military code signals do not have a fixed frequency.[95] Furthermore, they can also boost the power of some military signals, making them more resistant to jamming.[96] Finally, they have the selective availability capability.

Block IIF satellites are the newest GPS satellite generation. The 12 Block IIF satellites make up approximately 39 percent of GPS's 31 satellite constellation.[97] They all started operations between 2010 and 2016.[98] They have a 12-year design life, which is 64 percent greater than the design life of 7.5 years of previous generations.[99] They broadcast all of same signals as the Block II R

[90] Ibid.

[91] Ibid.

[92] Ibid.

[93] Ibid.

[94] Ibid.

[95] Ibid.

[96] Ibid.

[97] Ibid.

[98] Ibid.

[99] Ibid.

(M) satellites.[100] In addition, they broadcast a third civil signal.[101] Finally, the U.S removed the selective availability capability from these satellites.

### 2. Control Segment

The control segment monitors and manages the performance of the GPS satellite constellation.[102] It consists of three main elements: 2 master control stations, 15 monitoring stations, and 11 ground antennas.[103] Figure 1 shows where these ground facilities are located.[104]

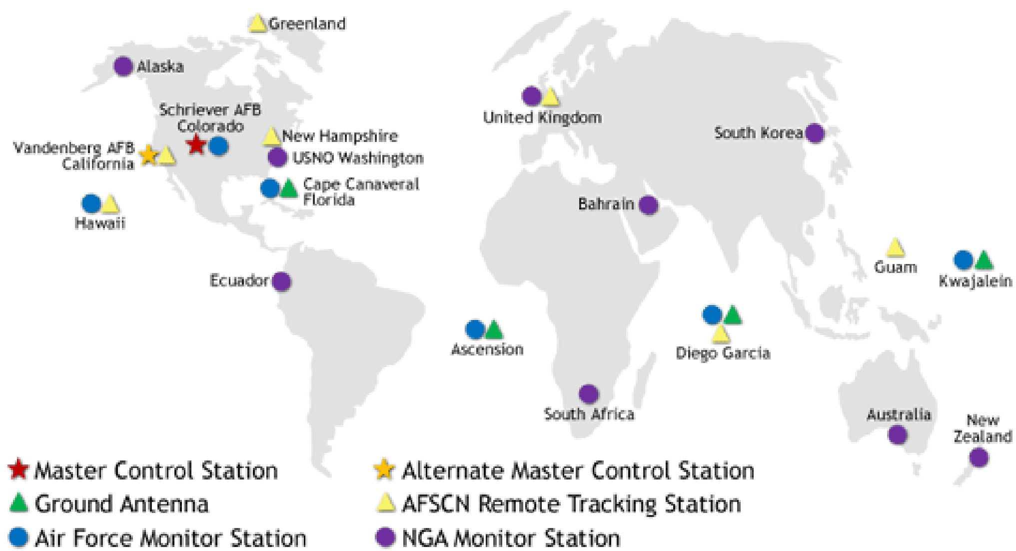


Figure 1. GPS Ground Control Segment[105]

The master control station manages the operation of the GPS satellite constellation. It receives satellite tracking and atmospheric data from the 15

[100] Ibid.

[101] Ibid.

[102] DOD, *Global Positioning System*, 5–6.

[103] National Coordination Office, "Control Segment."

[104] Ibid.

[105] Source: National Coordination Office, "Control Segment."

globally distributed monitoring stations.[106] The master control station(s) uses the 11 globally distributed ground antennas to synchronize GPS's satellite clocks, upload navigation information, and if necessary issue orders to adjust satellite operations.[107]

### 3. User Segment

The GPS user segment consists of all organizations and individuals that use GPS receivers.[108] For national security reasons, the U.S. has divided the GPS user segment into two different groups: military and civil.[109] This approach provides two major benefits; it protects GPS military signals from interference while at the same time making GPS's civil signals available for everyday use.

Military users operate using encrypted GPS signals. They employ sophisticated GPS receivers and antennas that are not publicly available.[110] Furthermore, military GPS receivers operate using utilize multiple signals allowing them to make additional corrections to their estimates of location, course, speed, and altitude.[111] Collectively, these factors make military GPS signals more resistant to enemy jamming, false broadcasts, and natural signal interference then civil GPS signals.

Civil GPS users consist of organizations and individuals who use GPS's unencrypted civil signals.[112] They use less sophisticated receivers and antennas than military users. Many users of civil GPS receivers utilize one set of GPS signals, which means they cannot develop and apply correction to improve signal

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106 Ibid.

107 Ibid.

108 National Coordination Office, "The Global Positioning System."

109 Congressional Budget Office [CBO], *The Global Positioning System for Military Users: Current Modernization Plans and Alternatives* (Washington DC: Congressional Budget Office, 2011), http://www.cbo.gov/publication/42727, 1–3.

110 Ibid., 37–43.

111 National Coordination Office, "GPS Accuracy," last modified August 31, 2016, http://www.gps.gov/systems/gps/performance/accuracy/.

112 CBO, *The Global Positioning System*, 1–2.

accuracy.[113] Furthermore, foreign militaries and manufacturers have developed jammers that can interfere with GPS signals over small and large areas.[114] As a result, civil GPS users have a higher level of vulnerability to intentional and unintentional interruptions in service than military GPS users.

## B. GPS AUGMENTATIONS

GPS's basic civil signal is not sufficient for applications require precise navigation information such as commercial aviation and marine shipping.[115] Therefore, the U.S. operates and participates in several domestic and international augmentation efforts that improve the accuracy and reliability of the standard GPS signal.

Table 2 shows the U.S.' five federally funded and/or supported GPS augmentation systems. Each of these augmentations serves a specific navigation region and purpose. Moreover, all of these systems rely on GPS's unencrypted standard positioning signal. This means these augmentation systems will not operate if GPS service is interrupted.

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[113] National Coordination Office, "GPS Accuracy."

[114] PNT, *Jamming the Global Positioning System*, 4–6; CBO, *The Global Positioning System*, 41–42.

[115] White House, *NSPD-39*; DOD, DHS, and DOT, *2014 Federal Radio Navigation Plan*, 5-9.

Table 2. U.S. GPS Augmentation Systems

| Augmentation | Regions Served | Primary Use |
|---|---|---|
| Nationwide Differential GPS | U.S. | Marine and surface transportation |
| Wide Area Augmentation System | North America | Commercial aviation |
| Continuously operating reference stations | U.S., Caribbean, Central America | Surveying and monitoring |
| Global differential GPS | International | Space applications and commercial aviation |
| International Global Satellite Systems Service | International | Earth science and geodesy |

Three of the augmentation systems provide service to North American GPS users. The Nationwide Differential Global Positioning System consists of 46 sites within the U.S that provide GPS signal corrections to surface and marine users.[116] The Wide-Area Augmentation System consisting of two operational control centers, three master stations, three geostationary satellites, six ground stations, and 38 reference stations, and three geostationary satellites that provide signal corrections to North American commercial aviation.[117] The Continuously Operation Reference Stations (CORS) network is a consortium of over 200 institutions operating approximately 2000 stations throughout the U.S., the Caribbean, and Central America.[118] Using the data from the CORS network,

[116] Office of the Assistant Secretary for Research and Technology, U.S. Department of Transportation, "Nationwide Differential Global Positioning System (NDGPS) Program," accessed August 21, 2016, http://www.rita.dot.gov/pnt/major_initiatives/nationwide_differential_gps_major_initiative.html.

[117] Jason Burns, *Wide Area Augmentation System (WAAS)—Program Status Update* (Washington, DC: Federal Aviation Administration, 2013), http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/briefings/media/WAAS_RTCA_brief_31213.pdf, 2.

[118] National Geodetic Survey, "Continuously Operating Reference Station," last modified August 24, 2015, http://www.ngs.noaa.gov/CORS/; National Geodetic Survey, "CORS MAP," last modified February 12, 2015, http://www.ngs.noaa.gov/CORS_Map/.

the U.S. develops and distributes GPS signal improvements for positioning, navigation, meteorology, and geophysics.[119]

The U.S. also participates and supports two international GPS augmentations systems: Global Differential GPS (GDGPS) and the International Global Navigation Satellite Service (IGS). GDGPS provides corrections to U.S. Chinese, European Union, and Russia satellite navigation signals.[120] In addition, it facilitates U.S. aviation and space operations, improves the navigation capabilities of mobile devices, and allows public safety agencies to determine the location of emergency cellular phone calls.[121] The IGS is an international effort consisting of over 200 organizations focused on using data from the world's satellite navigation systems to improve satellite orbits and to scientifically measure the Earth's shape, rotation, and atmospheric conditions.[122]

GPS and it augmentations are important navigation and timing systems. They provide vital signals to the national and homeland security of America and many other nations. Moreover, GPS signal interruptions can stop or degrade the operations of critical military and civilian systems. Therefore, the U.S must prevent and mitigate the consequences of GPS outages. Examination of GPS and its augmentations from the perspective of a public utility (Chapter IV) as well as that of a software platform (Chapter V) can provide additional insights about criticality, resilience, and vulnerability. This new knowledge may help the U.S. more effectively prevent and mitigate GPS disruptions.

[119] Richard Snay, "The National & Cooperative CORS Program" (presented at CORS Users Forum, Silver Spring, MD, April 19, 2002), http://www.ngs.noaa.gov/CORS/Presentations/CORSForum2002/snay.pdf, 5–6.

[120] Jet Propulsion Laboratory California Institute of Technology [JPL], "System Description—Overview," last modified February 4, 2016, http://www.gdgps.net/system-desc/index.html.

[121] Jet Propulsion Laboratory California Institute of Technology [JPL], "The Global Differential GPS System Applications," last modified December 16, 2015, http://www.gdgps.net/applications/index.html.

[122] International GNSS Service, "IGS About," 2016, http://www.igs.org/about.

# IV. THE PUBLIC UTILITY CONCEPTUAL LENS

This chapter develops and applies a public utility conceptual lens to examine in what ways GPS operates as a physical infrastructure that produces and delivers essential goods or services to its users.[123] Moreover, it examines economic and infrastructure conceptualizations and definitions of public utilities to develop a lens to explain how a physical infrastructure salient characteristics influence its operations, vulnerabilities, and protection strategies. Then, it examines to what extent GPS conforms to the public utility lens. Finally, it discusses how the public utility lens informs our understanding of GPS's criticality, resilience, and vulnerabilities.

## A. THE PUBLIC UTILITY CONCEPTUAL LENS

The public utility lens provides a framework to examine how a physical infrastructure's major characteristics influence its operations, vulnerabilities, and protection strategies. There is no one definition that can be used to fully describe a public utility's major traits, processes, weaknesses and protection strategies.[124] Public utilities include a broad range of regulated and unregulated industries, which, in terms of their major characteristics, can be indistinguishable from unregulated firms.[125] This means that the criteria used to commonly define a public utility may not always be valid. Examination of several public utility definitions from the economics and critical infrastructure fields overcomes this limitation by providing a broader perspective in identifying the most salient public utility characteristics.

[123] President's Commission on Critical Infrastructure Protection, *Critical Foundations Protecting Americas Infrastructure. The Report of the President's Commission on Critical Infrastructure Protection* (Washington DC: President's Commission on Critical Infrastructure Protection, 1997), http://fas.org/sgp/library/pccip.pdf, B-2; Investor Words, "Infrastructure," accessed July 6, 2016, http://www.investorwords.com/2464/infrastructure.html.

[124] Bonbright, *Principles of Public Utility Rates*, 3.

[125] Ibid., 3–17.

### 1. Economics

Economists have defined public utilities in four different ways: general purpose technologies, natural monopolies, regulated enterprises, and physical networks. Each of these definitions provides different insights on the major traits of public utilities. Public utilities, such as electricity and railroads, can be considered general purpose technologies.[126] They are widely used, have demonstrated significant improvement, and spurred the development of new products and services.[127] Firms and other infrastructures in an area can improve their productivity by purchasing equipment and services allowing them to incorporate a public utility's output into their operations.[128] In turn, businesses conduct additional research and make development investments, which over time, improve the public utility, existing products and services, and lead to creation of new products and services.[129] This definition implies that if a public utility's service is interrupted, every firm in the affected region could suffer economic losses.

Public utilities, like electric companies and water authorities, have been historically defined and treated as a regulated monopoly provider of good or service.[130] Geddes indicates the reason for this is that public utilities historically have been considered natural monopolies.[131] A major characteristic of a natural

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[126] Richard G. Lipsey, Kenneth I. Carlaw, and Clifford T. Bekar, *Economic Transformations* (New York: Oxford University Press, 2005), Kindle edition, Kindle locations 2925–3119; Boyan Jovanovic and Peter L. Rousseau, "General Purpose Technologies," in *Handbook of Economic Growth*, Vol. 1, ed. Philippe Aghion and Steven Durlauf (Amsterdam, Netherlands: Elsevier B.V., 2005), 1184.

[127] Jovanovic and Rousseau, "General Purpose Technologies," 1184–1186; Timothy F. Bresnahan and Manuel Trajtenberg, "General Purpose Technologies 'Engines of Growth?,'" *Journal of Econometrics* 65, no. 1 (1995): 83–84.

[128] Elhanan Helpman and Manuel Trajtenberg, *A Time to Sow and a Time to Reap: Growth Based on General Purpose Technologies* (Cambridge, MA: National Bureau of Economic Research, 1994), 1–2; Elhanan Helpman and Manuel Trajtenberg, *Diffusion of General Purpose Technologies* (Cambridge, MA: National Bureau of Economic Research, 1996), 1–3.

[129] Helpman and Trajtenberg, *A Time to Sow*, 1–2; Helpman and Trajtenberg, *Diffusion of General Purpose Technologies*, 1–3.

[130] Geddes, "Public Utilities," 1162.

[131] Ibid., 1165.

monopoly is that they are believed to produce economies of scale—an outcome in which a firm's average production cost declines over its entire range of output.[132] Public utilities have been considered natural monopolies because they incur high fixed costs due to operating and maintaining the physical infrastructure necessary to provide their customers with service.[133] These average fixed costs decline as they are spread over more customers.[134] Therefore, governments regulate public utilities to maintain their economies of scale and to limit the unnecessary infrastructure duplication that would result from competition.[135] However, this comes with two potential risks. One, it can make a region more dependent on a utility as there is an incentive to maximize its use. Two, it can limit a region's resiliency as it does not allow competitors to build additional infrastructure.

Bonbright asserts a public utility is simply an enterprise requiring government regulation to establish and maintain the physical connection between its infrastructure and customer.[136] A public utility, such as an electric company, cannot provide its customers with their products and services without this connection. Furthermore, he argues that a firm should not be considered a utility simply because it has economies of scale and produces an essential product.[137] These criteria are of limited usefulness because regulated and unregulated firms often demonstrate these characteristics.[138] In other words, public utilities and private business can produce vital goods and services as well as achieve economies of scale.

[132] Geddes, "Public Utilities," 1164; Ben W. F. Depoorter, "Regulation of Natural Monopoly," in *Encyclopedia of Law and Economics*, ed. Boudewijn Bouckaert and Gerrit De Geest (Cheltenham, UK: Edward Elgar, 2000), 499, http://encyclo.findlaw.com/5400book.pdf, 499.

[133] Depoorter, "Regulation of Natural Monopoly," 498.

[134] Ibid.

[135] Geddes, "Public Utilities," 1165; Depoorter, "Regulation of Natural Monopoly," 498.

[136] Bonbright, *Principles of Public Utility Rates*, 12–13.

[137] Ibid., 7–17.

[138] Ibid., 7–11.

Analysis of Bonbright's arguments suggests three conditions must be met for a firm to be considered a public utility. One, a firm must require a permanent physical connection with its customers in order to provide them with continuous service or supply of vital products.[139] Two, government regulations are required to establish and maintain these physical connections between a firm and its customers.[140] Three, the government in the interest of protecting the public and/or promoting the abundance of a vital good or service directly controls the prices a firm can charge its customers.[141] Bonbright's arguments suggest government regulation of a utility may be necessary, but it may also make a nation or region overly dependent on a public utility's output.

Geddes points out there are many different types of public utilities, such cable television, railroads, and telecommunications, and that they tend to have large infrastructures.[142] Governments or private firms can own some or all of this infrastructure.[143] Moreover, these infrastructures are actually networks, which can be broken into three elements: production, transmission, and distribution.[144] The production element creates a good or service.[145] The transmission and distribution elements transport the goods or services to the utility's customers.[146] These physical networks may not operate if one of more of their elements is rendered inoperable. Implicit in Geddes's discussion is that a utility may not be able to operate if one or more of the elements stops working and/or the network is severed.

139 Ibid., 4.

140 Ibid., 12.

141 Ibid., 4, 9.

142 Geddes, "Public Utilities," 1162.

143 Ibid., 1163–1164.

144 Ibid.

145 Ibid., 1163.

146 Ibid.

According to Geddes, a utility's three elements can be owned and operated by one firm or many firms.[147] This implicitly raises the possibility that when a government is determining if and how a utility is regulated that it makes a tradeoff between its costs and resiliency. One firm may be able to operate a utility in a very cost-effective manner. This may be the result of regulatory and/or market conditions that in effect create entry barriers preventing other firms from entering the utility's market. This in turn can constrain a utility's resiliency as it limits the amount of additional infrastructure that may be built as a result of competition.

### 2. Critical Infrastructure

The critical infrastructure literature broadens the concept of a utility to include external factors, such as people and regulations, that influence the nature of its operations. An examination of two different infrastructure definitions provides support for how the economics literature has conceptualized public utilities.

Jonsson has developed a concept of infrastructure systems that provides an expanded view of a utility. He notes that infrastructure systems are like public utilities in that they provide society with products and services, such as electricity and water, that improve the quality of life.[148] They distribute and deliver "specialized services, materials, and assets to households, companies and other organizations."[149] Moreover, they are designed to quickly, cheaply, and reliably produce one type of product or service.[150] They serve as the foundation of secondary services, such as firefighting and laundry service with water systems, which rely on infrastructure system.[151] Furthermore, they are used in

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[147] Ibid., 1164.

[148] Daniel Jonsson, "Sustainable Infrasystem Synergies: A Conceptual Framework," *Journal of Urban Technology* 7, no. 3 (2000): 82.

[149] Ibid.

[150] Ibid., 83.

[151] Ibid., 89.

combination with other infrastructure systems.[152] However, these systems are different then public utilities as they include "the organizations and people, who use, build and operate the system and the economic and legal conditions for the activities."[153]

The infrastructure definition of U.S. Department of Homeland Security (DHS) also provides an expanded view of utilities:

> The framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the United States the smooth functioning of Government at all levels, and society as a whole.[154]

DHS recognizes that infrastructures are equivalent to public utilities in that they can consist of networks delivering vital goods and services to their customers. Moreover, it acknowledges that multiple utilities work together to provide all of the essential products and services that a nation requires to function. Finally, it also recognizes infrastructures as physical networks.

The infrastructure definitions of Jonsson and DHS provide support for both the economics and infrastructure public utility definitions. They both support the notion that public utilities are general purpose technologies that serve as a regional and national economic foundation. Additionally, they acknowledge that factors external to public utility operations, such as people and organization, can have an impact on a public utility's performance. Jonsson in particular notes the efficiency of public utilities in providing their services is a mixed blessing. Societies can become overly dependent on them, which can constrain their

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[152] Ibid., 83.

[153] Ibid.

[154] U.S. Department of Homeland Security, *NIPP 2013 Partnering for Critical Infrastructure Security and Resilience* (Washington, DC: U.S. Department of Homeland Security, 2013), https://www.dhs.gov/sites/default/files/publications/NIPP%202013_Partnering%20for%20Critical%20Infrastructure%20Security%20and%20Resilience_508_0.pdf, 31.

ability to address infrastructure related issues.[155] Finally, these definitions recognize public utilities are physical networks.

### 3. Summary: The Public Utility Len's Salient Characteristics and Protection Strategy

Four major salient characteristics emerge from examination of economics and critical infrastructure literature definitions of public utilities. First, public utilities are extremely important because they serve as the economic foundation of a nation and its regions. Second, the government regulation is required to establish and protect the physical connection necessary for a public utility to provide service to its customers. Three, government regulation of utility promotes a public utility's efficiency but may do so at the potential cost of its resiliency. Fourth, a public utility is a networked physical infrastructure that "provides service over large geographical areas."[156]

### 4. Public Utility Protection Strategy

A public utility must maintain a connection with its customers to provide them with continuous service. Public utilities are generally physical infrastructures, which means the impact of a service outage will generally be limited to the region served by the portion of network experiencing difficulty.[157] A public utility can use a mix of three approaches to prevent or lessen these impacts. One, it can maintain backups and/or redundant systems for facilities and equipment that would require significant time to fix should they fail.[158] Two, it could maximize the use of equipment that can be quickly repaired.[159] Third, it

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155 Jonsson, "Sustainable Infrasystem Synergies," 83.

156 Stephen J. Lukasik, *Review and Analysis of the Report of the President's Commission on Critical Infrastructure Protection* (Stanford: Center for International Security and Arms Control, Stanford University, 1998), 4.

157 Ibid.

158 National Infrastructure Advisory Council, *Critical Infrastructure Resilience: Final Report and Recommendations* (Washington, DC: National Infrastructure Advisory Council, 2009), https://www.dhs.gov/sites/default/files/publications/niac-critical-infrastructure-resilience-final-report-09-08-09-508.pdf, 12–13.

159 Ibid.

can encourage or require its customers to develop backups sufficient to meet their requirements during a service interruption.[160] This mix of approaches can minimize the likelihood and severity of an interruption in a public utilities operation.

## B. GPS AS A PUBLIC UTILITY

The public utility lens helps explain why the U.S. considers GPS to be a global utility critical to its "national security, economic growth, transportation safety, and an essential element of the worldwide economic infrastructure."[161] GPS conforms to all of major characteristics of the public utility's lens. Through its laws and policies, the U.S. has promoted GPS, transforming it from a navigation system to an economically important global utility. Moreover, it has treated GPS like a public utility in that it has made extensive use of redundancies to limit the geographic impact of service disruptions.

### 1. U.S. Laws and Policies Have Transformed GPS into a Global Utility

Through the development of its laws and policies, the U.S. has treated GPS like a global utility in that it has promoted GPS's use. For instance, U.S. Code Title 10, § 2281, Global Positioning, requires America provide GPS civil signals for "peaceful, civil, commercial, and scientific uses on a continuous worldwide basis free of direct user fees."[162] U.S. Code, Title 51 encourages the president to "enter into international agreements…to establish the Global Positioning System and its augmentations as an acceptable international standard."[163] Moreover, to maximize the world's use of GPS, the U.S. has made all of its technical specifications required to manufacture and use civil GPS

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[160] Ibid., 26–27.

[161] White House, *NSPD-39*.

[162] 10 U.S.C. § 2281.

[163] 51 U.S.C. § 50112 (2011), https://www.gpo.gov/fdsys/granule/USCODE-2011-title51/USCODE-2011-title51-subtitleV-chap501-subchapII-sec50112.

technologies freely available.[164] Furthermore, America has designed the GPS satellite constellation to provide continuous global signal coverage.[165] GPS civil signals are unencrypted, allowing anyone with a receiver to utilize them. Finally, the U.S. regulates and manages how its radio spectrum is used to prevent interference with the GPS signal, which serves as the link between GPS and its users.[166]

As a result of these efforts, GPS, like public utilities, has become a widely used technology; however, the U.S. does not keep official statistics on the number of GPS devices in operation or how they are used. European Union (E.U.) estimates and forecasts show GPS is and will most likely continue to be a widely used technology. The E.U. estimated in 2014 there were 3.6 billion satellite navigation devices.[167] Furthermore, the E.U has forecasted this number will grow to over 7 billion in 2019 – an increase of at least 94 percent.[168] It is not known how many of these devices GPS compatible are. It can be safely assumed the majority of them are GPS devices. Manufacturers have been producing consumer electronics with GPS capabilities since the 1980s.[169] Furthermore, E.U. market research indicates that 80 percent of all satellite navigation devices available for purchases are compatible with GPS.[170]

Preliminary studies of GPS economic importance highlight its value to the U.S. and the world. According to the U.S. Air Force, GPS has an annual

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[164] National Coordination Office, "Technical Documentation."

[165] National Coordination Office, "Space Segment."

[166] National Coordination Office for Space-Based Positioning, Navigation and Timing, "GPS Spectrum and Interference Issues," last modified February 9, 2015, http://www.gps.gov/spectrum/.

[167] European Global Navigation Systems Agency, *GNSS Market Report*, Vol. 4 (Luxemburg: Publications Office of the European Union, 2015), https://www.gsa.europa.eu/system/files/reports/GNSS-Market-Report-2015-issue4_0.pdf, 8.

[168] Ibid.

[169] Greg Milner, *Pinpoint How GPS Is Changing Technology, Culture, and Our Minds* (New York: W.W. Norton & Company, 2016).

[170] European Global Navigation Systems Agency, *GNSS Market Report*, 15.

operating budget of approximately one billion dollars.[171] In 2011, Pham calculated that in the United States alone GPS creates at least 67.6 billion dollars in direct economic benefits and that this value will increase to $122.4 billion when GPS reaches 100 percent use in "commercial GPS-intensive industries."[172] In 2013, Oxera Consulting released a report estimating that the geo services industry, which relies on satellite navigation systems and devices, globally generates between 150 and 270 billion dollars in revenue per year.[173] In addition, Leveson estimates in 2013 GPS's use in the U.S. produced between 37.1 and 74.5 billion dollars in economic benefits.[174]

GPS is also vital to the operation of America's three augmentations systems and two international consortiums, discussed in Chapter II. These systems are vital to America's transportation system, surveying, earth monitoring, and space operations. They remove errors from GPS signals, making them more suitable for activities with precise navigation requirements.[175] Each serves a vital purpose and set of users, and each of these systems requires GPS signals to operate, which means they may not be able to operate effectively during a GPS service interruption. During a GPS interruption, the Wide Area Augmentation System and Nationwide Differential Global Positioning System may not be able provide aviation, marine, and surface transportation users with the signal correction that improve their efficiency and safety.[176] If there were an

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[171] Bernard J. Gruber and Jon M. Anderson, "Space Superiority, down to the Nanosecond: Why the Global Positioning System Remains Essential to Modern Warfare," *Air & Space Power Journal* (September–October 2013): 98–119, http://www.au.af.mil/au/afri/aspj/digital/pdf/articles/2013-Sep-Oct/F-Gruber_Anderson.pdf.

[172] Nam D. Pham, *The Economic Benefits of Commercial GPS Use in the U.S. and The Costs of Potential Disruption* (Washington DC: NDP Consulting, 2011), 1.

[173] Oxera Consulting, *What Is the Economic Impact Geo Services* (Oxford, UK: Oxera Consulting, 2013), http://www.oxera.com/Oxera/media/Oxera/downloads/reports/What-is-the-economic-impact-of-Geo-services_1.pdf?ext=.pdf, iv.

[174] Irv Leveson, "The Economic Benefits of GPS," *GPS World*, September 2015, – http://gpsworld.com/the-economic-benefits-of-gps/, 36.

[175] National Coordination Office for Space-Based Positioning, Navigation and Timing [National Coordination Office], "Augmentation Systems," last modified July 5, 2016, http://www.gps.gov/systems/augmentations/.

[176] Ibid.

interruption, the Continuously Operation Reference Stations (CORS) Network and International Global Navigation Satellite Service may not be able to provide the signals required for surveying, earthquake monitoring, and other activities requiring extreme precise navigation accuracy.[177] Similiarly, the Global Differential GPS system may not be able to provide signal correction necessary for space operations, mobile device navigation, and location of emergency cellular phone calls in the event of a GPS interruption.[178]

### 2. GPS Infrastructure is designed to Prevent and Minimize Disruption

Like a public utility, GPS is designed and operated in a manner that seeks to prevent and limit the frequency and severity of service interruptions; however, it is different from a public utility in two fundamental ways. One, it operates using radio signals, which means it is not physically connected with its users. Two, it is designed and operated in such a manner that every individual element of its control (ground infrastructure) and space segments contributes to the global production GPS signals. This creates extensive redundancies within the GPS system. Together, these characteristics suggest GPS infrastructure failures are unlikely and will most likely have little to no impact on GPS's operations.

All GPS's ground infrastructures are different from public utility production facilities in that they help create and transmit satellite signals for all of its users. Its 11 command and control antennas collect satellite telemetry data,[179] While its 15 monitoring stations track GPS satellites and gather data on atmospheric conditions.[180] A master control station uses this data to develop signal corrections, which improve the accuracy of GPS signals. Furthermore, a master

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[177] U.S. National Oceanic Atmospheric Administration [NOAA], "Continuously Operating Reference Station (CORS)," last modified August 24, 2015, http://www.ngs.noaa.gov/CORS/; John M. Dow, Ruth E. Neilan, and Chris Rizos, "The International GNSS Service in a Changing Landscape of Global Navigation Satellite Systems," *Journal of Geodesy* 83, no. 3–4 (March 2009): 191.

[178] JPL, "The Global Differential GPS System Applications."

[179] National Coordination Office, "Control Segment."

[180] Ibid.

control station uses the command and control antennas to upload these signal corrections and other navigation data to each GPS satellite.[181] Finally, the master control station also provides each satellite with sufficient data to operate without ground control for up to 60 days.[182]

GPS's control segment has significant redundancies, which like those of a public utility, limits the likelihood and consequences of a service interruption. GPS requires a minimum of two master control stations, four command and control antennas, and six monitoring stations to meet its performance requirement of worldwide satellite availability 95 percent of the time.[183] It currently has two master control stations, 11 command and control antennas, and 15 monitoring stations. It also has seven (75 percent) more antennas and nine (150 percent) more monitoring sites than necessary.[184] This infrastructure is globally distributed across the world. Due to the redundancies, GPS can endure a significant amount of failure within its ground infrastructure and still be able to monitor and control GPS's operations. Finally, GPS satellites can still continue to operate for an extended period of time after the entire ground infrastructure is lost.

The space segment continues the production and distribution while at the same time minimizing the likelihood of signal interruptions. Each of GPS's operational satellites are continuously generating and broadcasting its navigation signals. GPS users require signals from four different satellites for navigation and one satellite signal for timing.[185] To meet these requirements and provide global

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[181] Ibid.

[182] Office of the Chair of the Joint Chief of Staff, *Space Operations* (Joint Publication 3-14) (Arlington, VA: U.S. Joint Chiefs of Staff, 2013), http://dtic.mil/doctrine/new_pubs/jp3_14.pdf, E-14.

[183] Assistant Secretary of Defense for Command, Control, Communications, and Intelligence [ASD(NII)], *Global Positioning System Standard Positioning Service Performance Standard* (Washington DC: U.S. Department of Defense, 2001), 3, 13.

[184] National Coordination Office, "Control Segment."

[185] Jean-Marie Zogg, *GPS Basics Introduction to the System Application Overview* (Switzerland: u-blox, 2002), 12–15.

signal coverage, every satellite is constantly moving around the Earth to guarantee global signal coverage.[186] As a result, the combinations of GPS satellites available for navigation are constantly changing as each satellite progresses through their individual orbits.[187] This means that should a satellite failure occur, the time a poor satellite combination occurs will be minimized.

The GPS satellite constellation has significant redundancies to increase its reliability as a public utility. A minimum of 24 GPS satellites is required to provide users with signals from four different satellites—the minimum required for navigation. The current 31 satellite constellations provide users with signals from six satellites.[188] This means two satellite failures can occur, and most users will still be able to continue using GPS for navigation. Furthermore, the likelihood of a GPS satellite failure is small. Each satellite has redundant backup for every critical system. For example, each GPS satellite has three atomic clocks when only one is needed for its operation.[189] Finally, the U.S. can reactivate decommissioned satellites or rearrange the GPS satellite constellation if several satellite failures occur.

## C. THE PUBLIC UTILITY LENS AND GPS'S CRITICALITY, RESILIENCE, AND VULNERABILITY

The U.S. considers GPS to be a global information utility and one of its most important critical infrastructures.[190] The public utility lens shows GPS is a general purpose technology and an infrastructure that does not require a fixed physical connection with its users to operate. This is because signals serve as

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[186] National Coordination Office, "Space Segment."

[187] Forden, "Viewpoint: China and Space War," 144–145.

[188] Integrated Mapping Ltd, "How GPS Works," Maptoastertopo, accessed July 23, 2016, https://www.maptoaster.com/maptoaster-topo-nz/articles/how-gps-works/how-gps-works.html.

[189] United States Naval Observatory, "Block II Satellite Information," United States Naval Observatory, March 9, 2016, ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt.

[190] White House, *NSPD-39*; White House, *Homeland Security Presidential Directive-7: Critical Infrastructure Identification, Prioritization, and Protection* (Washington, DC: White House, 2003), https://www.dhs.gov/homeland-security-presidential-directive-7; U.S. Department of Homeland Security, *National Infrastructure Protection Plan* (Washington DC: U.S. Department of Homeland Security, 2006), https://www.hsdl.org/?view&did=459572.

the link between the GPS satellite constellations and its receiver's connection. Moreover, it begins to help explain how the U.S. has influenced the nature of GPS's criticality, resilience, and vulnerabilities through its laws, polices, and GPS's design.

The public utility lens shows that through its laws and policies, America has transformed GPS from satellite navigation systems to a critical global infrastructure. It suggests the U.S. did this by addressing three of the biggest constraints to the adoption and diffusion of general purpose technologies that are utilities: infrastructure, technical knowledge, and cost. Historically, a lack of infrastructure and skilled workers limited the spread of general purpose technologies. Firms and households could not use a utility if the infrastructure required to use it was not present.[191] Furthermore, there was not a sufficient number of workers with the knowledge required to build and use the utility.[192] Finally, the cost of adopting a public's utility's service was often financially unfavorable as the existing technology was still profitable.[193]

In effect, America has accelerated GPS's growth as a general purpose technology by addressing all of the constraints to adoption and diffusion. It has provided the world with the entire infrastructure required for global satellite navigation when it built GPS. Firms and individuals can begin using GPS by simply purchasing a GPS receiver. They did not have to wait for physical infrastructure to be built in their region. Moreover, The U.S. has supplied the knowledge necessary to use GPS by making all technical specifications freely available. Any firm or entrepreneur with the desire to do so can develop GPS related products and services. Finally, America addressed the cost concerns by making GPS civil signals available free of charge; anyone who has a receiver can use GPS.

[191] Jovanovic and Rousseau, "General Purpose Technologies," 1190.

[192] Paul A. David, "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox," *The American Economic Review* 80, no. 2 (1990): 358.

[193] Ibid., 357.

The public utility lens reveals the U.S. has used system design and redundancies to improve GPS's resilience. America has broadly distributed GPS's satellite signal production, transmission, and distribution functions among all of its major elements in its ground and space infrastructures. This has two major benefits. It means that every individual system component is contributing to the global production of satellite signals. Furthermore, as a result of this design approach, the U.S. has improved GPS's resilience by reducing the criticality of every individual element involved in the production and delivery of satellite signals to its users. Finally, the U.S. has further reduced this criticality by adding more satellite and ground infrastructure than is required for GPS to meet its minimum operating requirements. Collectively, these design decisions have reduced GPS's vulnerability to major service disruptions.

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# V. THE SOFTWARE PLATFORM CONCEPTUAL LENS

This chapter develops and uses a software platform conceptual lens to examine the ways GPS operates as a computer operating system, allowing programs to run on hardware.[194] First, it provides a general definition of a software platform and describes how the interaction between its three architectural elements determines the scope and scale of its use. Next, it evaluates the structure of the GPS system to determine in what ways its major components correspond to and function like those found in a software platform's architecture. Lastly, it explains how the software platform lens informs our understanding of GPS's criticality, resilience, and vulnerability.

## A. THE SOFTWARE PLATFORM CONCEPTUAL LENS

The software platform conceptual lens focuses on the relationships between a computer operating system, applications, hardware, and the end users.[195] A software platform uses an operating system's digital code to provide programmers with the capability to develop applications that run on hardware.[196] Software platforms provide their end users with computing devices that can perform a wide range of general and specialized tasks.[197] A platform's technological architecture consists of three main elements: an operating system, complements, and interfaces.[198] The interaction between these elements determines the scope and scale of a software platform's use.[199]

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[194] David S. Evans and Richard Schmalensee, *Matchmakers: The New Economics of Multisided Platforms* (Boston, MA: Harvard Business Review Press, 2016), Kindle edition, Kindle location 3687–3694.

[195] Ibid.

[196] Evans and Schmalensee, *Matchmakers*, Kindle location 3686; Evans, Hagiu, and Schmalensee, *Invisible Engines*, Kindle locations 79–96.

[197] Tiwana, *Platform Ecosystem Aligning Architecture*, 5–6.

[198] Evans and Schmalensee, *Matchmakers*, Kindle locations 3693–3697; Carliss Y. Baldwin and C. Jason Woodard, *The Architecture of Platforms: A Unified View* (Working Paper 09-034) (Cambridge, MA: Harvard Business School, 2008), http://www.hbs.edu/faculty/Publication%20Files/09-034_149607b7-2b95-4316-b4b6-1df66dd34e83.pdf, 20.

[199] Baldwin and Woodard, "The Architecture of Platforms," 21–22.

A software platform's operating system provides application developers and end users with a general set of computing capabilities.[200] These consist of a core set of programs and hardware, which relative to the rest of the software platform elements, changes slowly over time.[201] Application developers, peripheral manufacturers, and consumers benefit from this relative stability. Without creating entirely new code, programmers and hardware companies can create new products and services based on an operating system's functions.[202] Customers can customize and/or add more capabilities to their computing devices by purchasing these new items.[203] A lack of stability in an operating systems programs and hardware can constrain the amount of value a software platform provides to all of its participants.

A software platform's complements are the set of applications and peripherals that are allowed to change at a faster rate than its operating system.[204] They are new programs and/or devices that provide specialized capabilities not present in an operating system.[205] In other words, they increase a software platform's capabilities. Additionally, they operate using new code that must work with an operating system's software and hardware in order to function.[206] This is very advantageous. Application developers and peripheral manufacturers can create new products and services without having to develop their own operating systems.[207] Moreover, this can significantly increase the number of firms creating new software platform products and services.[208]

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[200] Tiwana, *Platform Ecosystem Aligning Architecture*, 65.

[201] Baldwin and Woodard, "The Architecture of Platforms," 20–21.

[202] Tiwana, *Platform Ecosystem Aligning Architecture*, 5.

[203] Ibid., 67.

[204] Baldwin and Woodard, "The Architecture of Platforms," 21.

[205] Tiwana, *Platform Ecosystem Aligning Architecture*, 5–6.

[206] Ibid., 65–66.

[207] Ibid.

[208] Ibid.

Interfaces are programs and devices that allow a software platform's operating systems and complements to operate with each other.[209] Operating system and compliment owners can develop their own interfaces. The benefit of interfaces is that they can make the elements software platform interchangeable.[210] That is, they allow for operating systems and complements to change without undermining the platform's performance.[211] In addition, they can increase the opportunities for the new platform innovations. Programmers and hardware manufacturers can use the existing code of operating systems and/or complements as the foundation for new products or services.[212] Specifically, they do not have to write a significant amount of new code. Interfaces like computer operating systems tend not to change because they allow innovation to occur while maintaining the software platform's functions and design.[213]

The interactions between a software platform's core, complement, and interfaces play a major role in the scale and scope of its use. Stable operating systems and interfaces allow platform and compliment owners to easily reuse and bundle code.[214] This provides them with the ability to increase the scale of a platform's use by lowering prices to attract new customers.[215] Moreover, as a result of this customer increase, computer programmers and hardware manufacturers may decide to participate in a software platform's market.[216] They can increase a platform's scope by creating new products and services that add capabilities. This in turn can creates a positive feedback loop—new platform

209 Baldwin and Woodard, "The Architecture of Platforms," 9–10.

210 Ibid., 2.

211 Ibid., 9.

212 Ibid., 8–9.

213 Ibid., 21–22.

214 Ibid., 3.

215 Ibid., 4.

216 Tiwana, *Platform Ecosystem Aligning Architecture*, 36.

customers can attract new application developers and hardware firms to a platform, which can result in new product and services.[217]

## B. GPS AS A SOFTWARE PLATFORM

The software platform conceptual lens provides a limited explanation of how GPS operates as a commercial technology. The U.S. has chosen to operate GPS as an open platform; there are no “major restrictions of its development, commercialization or use.”[218] U.S. laws and policies are designed to maximize GPS’s commercial use. Furthermore, America provides GPS’s civil signals and technical specifications free of charge.[219] However, the U.S. has chosen not to govern GPS commercial software platform. Instead, America operates and maintains GPS and its augmentation systems as a federally-owned navigation platform that others can use for public and private purposes.

### 1. GPS: A Navigation Operating System

GPS’s signals, receiver software, satellite constellations, and ground infrastructure serve as an operating system to an American navigation platform. Together, these elements provide GPS users with the capability to determine precise time and to estimate their location, course, speed, and altitude.[220] Moreover, they serve as the foundation of America’s navigation platform.

Broadly considered, the stable set of programs of GPS’s operating system consists of its satellite signals and receiver software. Every specific type of GPS navigation signal has its own format for the time and navigation data it

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217 Ibid.

218 Thomas R. Eisenmann, Geoffrey Parker, and Marshall Van Alstyne, *Opening Platforms: How, When and Why?* (Working Paper 09-030) (Cambridge, MA: Harvard Business School, 2008), 1. The U.S.’ only restrictions on GPS are nation security related. GPS receivers or component with the following characteristics are subject to U.S. Import and Export laws: use military GPS signals, operate with anti-jamming antennas, operate on large drones, rockets and missiles. U.S.C. Title 22, ch. 1, subch. M, § 121.1.

219 10 U.S.C. § 2281; National Coordination Office for Space-Based Positioning, Navigation and Timing, “Technical Documentation.”

220 Zogg, *GPS Basics Introduction*, 11–15.

contains.[221] Each signal can be considered software because it contains instructions and data, which a GPS receiver uses to process it.[222] Furthermore, each GPS receiver contains software, allowing it to recognize, digitize, and transform these signals into navigation information.[223] GPS receivers cannot operate if these signals change or if they do not have the internal software to recognize and process them.

Satellites and ground facilities make up the stable set of hardware of GPS's operating system. This combination of infrastructure is designed to produce the information and signals GPS receivers need to operate. Every GPS satellite flies in a specific orbit, broadcasts a specific set of navigation signals, and has a service life between 7.5 and 15 years.[224] Moreover, GPS's terrestrial facilities collect and provide the data and information necessary to support the production and broadcast of the existing set of navigation signals.[225] Existing GPS receivers are designed to operate without the current set of satellite signals and their supporting ground infrastructure.

From a software platform perspective, the U.S. has improved GPS's service by adding new software and hardware. It has specifically added more signals and ground infrastructure than what is required for the system to operate. This approach is beneficial because it maintains GPS's backward and forward capability and compatibility. Receivers and processes relying on an older set of civil signals can continue to operate in their normal fashion. However, their resilience and vulnerabilities do not change because they are not designed to use these newer signals. However, new devices and services that make use of

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221 European Space Agency, "GPS Navigation Message," *Navipedia*, January 20, 2015, http://www.navipedia.net/index.php/GPS_Navigation_Message.

222 Vangie Beal, "Software," *Webopedia*, accessed July 29, 2016, http://www.webopedia.com/TERM/S/software.html.

223 U.S. Air Force, *NAVSTAR Global Positioning System User Equipment* (Washington, DC: U.S. Air Force, 1996), 1-6–1-16.

224 National Coordination Office, "Space Segment."

225 National Coordination Office, "Control Segment."

older and newer signals can significantly increase their performance and resiliency. For this to happen, manufacturers and software developers would have to develop these products and services and consumers would have to purchase them.

### 2. GPS Augmentations As Navigation Platform Complements

The U.S. government operates three domestic augmentation systems and participates in two international augmentation consortiums. These augmentation systems like a software platform's compliments consist of programs and hardware to extend how GPS is used. They provide signal corrections that make GPS's civil signal's suitable for applications, such as commercial aviation, which requires precise navigation. Furthermore, they require an operating system's general functions to operate.

America's augmentations systems have software, signals, and other processes that depend on GPS signals. They each operate in a similar manner and evaluate how well a precisely located receiver estimates its position using GPS's signals.[226] From this comparison, the augmentation systems develop a set of signal corrections that are broadcasted to their users, provided on the internet, or shared by other means.[227] Each augmentation relies on software to perform these functions, and each of these systems supports a different GPS receiver.

These augmentations have infrastructures that can vary like a software platform compliment's hardware. The Wide Area Augmentation system has satellites and ground stations, which provide GPS signal corrections for civil aviation,[228] While the Nationwide Differential Global Positioning and Continuously Operation Reference Stations Network have terrestrial radio sites,

[226] Frederic G. Snider, *GPS: Theory, Practice and Applications* (Fairfax, VA: PDH Center, 2012), http://www.pdhonline.com/courses/l116/l116content.pdf, 20–21.

[227] Ibid., 20–24.

[228] U.S. Federal Aviation Administration, "Satellite Navigation."

which monitor GPS broadcasts and provide signal corrections for marine and surface users.[229] The International Global Navigation Satellite Service consists of satellite signal monitoring stations operated by organizations around the world.[230] Similarly, the Global Differential GPS system consists of sophisticated GPS receivers located across the world.[231]

## C. THE SOFTWARE PLATFORM LENS AND GPS'S CRITICALITY, RESILIENCE, AND VULNERABILITY

The U.S. government does not actively govern and operate GPS like a software platform. Instead, it operates GPS and its augmentation system like a computer operating system. To maintain and improve GPS's performance, it has also added new civil signals. In the short run, this approach does not change the nature of GPS's criticality, resilience, and vulnerability, though it might do so over time.

Through the addition of civil signals, the U.S. has transformed GPS into the functional equivalent of multiple satellite navigation systems. Each new set of signals increases its navigation accuracy and reliability by increasing the number of ways a GPS user can obtain time and calculate position, course, and speed. Every individual signal becomes less critical because there are more available for use. However, to receive these benefits GPS users must employ receivers that use multiple sets of signals. This is a somewhat uncertain outcome because manufacturers, application developers, and consumers do not have to choose these new signals. Furthermore, these signals do not change how GPS operates.

Multiple sets of signals provide the U.S. the opportunity to use market segmentation to improve the overall resilience of the population of GPS users. Each set of civil GPS signals provides its users with an inherent level of

[229] National Coordination Office, "Augmentation Systems;" NOAA, "Continuously Operating Reference Station."

[230] Dow, Nellan, and Rizos, "The International GNSS Service in a Changing Landscape of Global Navigation Satellite Systems," 191.

[231] JPL, "System Description—Overview."

resiliency. Through either cooperative efforts or regulation, the U.S. can develop receiver standards based on the criticality for the activity for which a GPS receiver is being used. This could help the U.S. make sure that critical economic sectors and infrastructure are less vulnerable to a GPS disruption.

# VI. CONCLUSIONS

The United States considers GPS a critical element of "national security, economic growth, transportation safety, and an essential element the worldwide economic infrastructure."[232] It provides vital timing and navigation signals to the U.S. military, allied armed forces, critical infrastructures, and vital economic sectors across the world. An interruption of GPS's operation could result in military setbacks, economic losses, accidents, and the loss of life and property.

To prevent these outcomes, the U.S. has made GPS extremely resilient to disruption. It flies more satellites than required, broadcasts multiple signals, and has added significant ground infrastructure to the GPS system.[233] Despite this, the president, Congress, federal agencies, and others have expressed concerns that there is a need for additional GPS backups. This raises the questions of: Why? And should more be done to address GPS's vulnerabilities?

The two lenses applied in Chapters IV and V focus on different aspects of the roles GPS fulfills as a global satellite navigation system. As a public utility, GPS is a physical infrastructure that produces and delivers critical navigation timing and signals to its users.[234] By contrast, as a software platform lens, GPS is an operating system that serves as foundation for navigation and timing applications.[235] These conceptual lenses represent two different but complementary characterizations of the GPS system. Each provides a different perspective on how GPS's most salient characteristics influence its operations, vulnerabilities, and the strategies used to protect it. Together, they provide us

232 White House, *NSPD-39*.

233 National Coordination Office, "Space Segment;" National Coordination Office, "Control Segment;" ASD(NII), *Global Positioning System Standard*, 3.

234 Black, *Oxford Dictionary of Economics*, 380; Geddes, "Public Utilities," 1162–1163; Deloitte Center for Energy Solutions, *Regulated Utilities Manual: A Service for Regulated Utilities* (Houston: Deloitte Development, 2012), http://ipu.msu.edu/library/pdfs/Deloitte%20Regulated%20Utilities%20Manual%20rebranded%20042012%20(1).pdf, 2–4.

235 Evans and Schmalensee, *Matchmakers*, Kindle locations 3687–3694.

with broader insights on the nature of GPS's criticality, resilience, and vulnerability.

## A. ANALYSIS

The U.S. has pursued two distinct strategies to address specific aspects of GPS vulnerabilities; together, they reveal that the U.S. has increased GPS resiliency by reducing the criticality of all of its major elements. The public utility lens suggests the U.S. has reduced GPS's vulnerability to service interruptions through system design and physical redundancies. The U.S. has designed GPS's operations so that every element in its ground and space infrastructure contributes the global production and delivery of GPS signals. In other words, these facilities outputs are not limited solely to the region in which they are located. This design approach creates redundancies in the GPS system as multiple ground facilities and satellites perform the same operational functions. Moreover, the U.S. has further increased GPS's resilience by increasing the number of GPS ground facilities and satellites. By doing this, the U.S. has added more redundancies to the GPS's infrastructure. System design and redundancies reduce the likelihood infrastructure failures will prevent GPS from providing its users with signals.

The software platform lens indicates America has decreased GPS's vulnerability by increasing the number of signals (e.g., computer code) in its operations. It has implemented this approach by increasing the amount of satellites in the GPS constellation. All GPS satellites broadcast a common set of signals. Furthermore, each new GPS satellite generation broadcasts a new set of set of signals in addition those of older generations. This means that the addition of new satellites to the GPS constellation automatically increases number and types of signals that are available for navigation. In others words, the GPS system has created redundancies in its signals. In the event that individual signals or set of signals is disrupted, GPS receivers have other broadcasts they can use to determine time or estimate their position, course, speed, and location. This assumes these receivers have the capability to use these newer signals.

Collectively, the public utility and software platform lenses suggest that manufacturers, programmers and end users are the major constraints in the U.S. approach to addressing GPS's vulnerabilities. Generally speaking, existing GPS devices are not reprogrammable and are only compatible with the satellites and signals that existed at the time they were manufactured. As a result, older GPS receivers and the processes that relying on them do not necessarily benefit from the addition of new satellite and signals. That is, they maintain their existing level of performance and vulnerability unless replaced with receivers that can use these newer signals. This means that the U.S. approach to improving GPS resilience depends on manufacturer and software programmer developing products and services that utilize GPS's older and new signals. Furthermore, consumers would have to purchase these new innovations.

## B. FINDING AND LIMITATIONS

There are two major shortcomings with the GPS research literature that limit the findings of this thesis. One, the social science and policy research communities have not made GPS a focus of sustained, theory-based research. Two, the U.S. does not keep official statistics on GPS use. Each of this limitation constrains this research in different ways.

The publicly available GPS literature does not evaluate GPS using theoretical concepts from the social sciences. As a result, the literature does not provide an in-depth explanation of what factors have made GPS such an important technology. Instead, the literature tends to simply describe GPS important as a global satellite navigation system. Consequently, there is not one overarching theoretical or conceptual framework that has been used to examine GPS and its relationship with the political, social, and technical factors that have influenced its evolution. Both time constraints and literature shortcomings have limited this thesis to a descriptive analysis how GPS conforms to public utility and platform lens. This is a small step toward a better understanding GPS, but more research to validate these findings would be beneficial.

There are no official statistics on the number of GPS devices in use and what economic and social activities they are supporting. This limits our ability to understand the scope and scale of GPS's use. In other words, it is not fully known how many and what type of GPS devices are currently in operation in America. Furthermore, it is also not known what quantities and types of GPS devices are being manufactured and sold to U.S. GPS users. These data limitations prevent us from having a complete understanding the full extent to which current and future users may be vulnerable to GPS service interruptions.

## C. NEXT STEPS

Social science research should be conducted on GPS to broaden our understanding of how military, economic, social factors have influenced its technological roles and vulnerabilities. Social construction of technology theory (SCOT), which has been used to study bicycle evolution, flood control, and nuclear weapons, would provide a useful starting point for this research.[236] It provides a framework and methodologies to determine how the interaction between a technology and groups has influenced how that technology is created, used, and improved.[237] This means SCOT can provide us with broader insights on how economic, political, and social process have shaped how the U.S. has designed, operated, and maintained GPS. Moreover, an understanding of the process can help the U.S. more effectively understand and addresses GPS vulnerabilities.

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236 Wiebe E. Bijker et al., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, anniversary ed. (Cambridge, MA: MIT Press, 2012), 11–44; Wiebe E. Bijker, "Why and How Technology Matters," in *The Oxford Handbook of Contextual Political Analysis*, ed. Robert E. Goodin and Charles Tilly (New York: Oxford University Press, 2009), http://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780199270439.001.0001/oxfordhb-9780199270439-e-037, 684.

237 Bijker, "Why and How Technology Matters," 684–685.

The U.S. government or research institution should lead the development of data collection systems models and metrics quantifying the number of GPS users and their vulnerabilities to interruptions in service. The ongoing U.S. public debate on GPS's vulnerabilities and how to best address them does not include numerical analysis. Sustained market research and surveys could provide data on number and the types of GPS devices in operation and/or being sold in America. Moreover, this data would allow for the development of quantitative models and metrics to estimate and track how GPS's use and vulnerabilities are changing over time. Furthermore, these models could help estimate the contributions that each major system element makes GPS's resilience. The knowledge and insights gained from this data, models, and metrics could help inform the public debate on GPS and future policy decisions.

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