The economic benefits of Global Positioning Systems (GPS)

Alan C. O’Connor
RTI International, USA

ABSTRACT

The Global Positioning System (GPS) delivers an extremely precise positioning, navigation, and timing signal to users around the world. Originally launched for U.S. military use, in the years since its signal was made available to the private sector, it has enabled innovators to develop a host of applications, services, and products. These advances have led to substantial gains in productivity, efficiency, and personal enjoyment.

From people driving to some place new to multinational corporations coordinating complex logistics networks, hundreds of millions of users rely on GPS every day for navigation and positioning. Its precision timing capability supports industries as diverse as finance, electricity, and telecommunications. Even the term *GPS* has entered the popular vernacular to mean one’s specific location at a specific point in time.

The ability to measure time intervals and frequencies extremely precisely is what allows GPS users to pinpoint their location anytime, anywhere in the world. The launch of Sputnik in 1957 and the resulting space race led the United States to accelerate scientific efforts deemed essential for national security

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and spaceflight capability, including the creation of what is today the Defense Advanced Research Projects Agency.

An important breakthrough occurred when U.S. researchers discovered they could discern the location of ground-receiving stations based on Sputnik's radio transmissions and accurately determine the satellite's orbit. That realization catalyzed research and development programs within the U.S. national laboratories, the military, and contractors in the private sector to develop satellite systems to further American geopolitical and defense interests. Programs from the 1950s and 1960s were combined in 1973 to form what is the GPS program today.

The analysis presented in this monograph focuses on the economic benefits of GPS to the U.S. private sector. We provide estimates from two perspectives. First, we quantified the value of GPS relative to alternative technologies and systems for the period from 1984 to 2017. Second, we estimated what the potential impacts would be if a GPS outage were to occur today. Our analysis combined insights from nearly 200 experts in the use of GPS for specific applications, surveys of professional surveyors and smartphone users, economic modeling tools, and national statistics. Benefits comprise productivity gains from new and existing products and services, improvements in quality, increases in personal enjoyment, and environmental and public health impacts.

1. Introduction

The Global Positioning System (GPS) is a network of monitoring stations and satellites that distributes a signal used for positioning, navigation, and timing (PNT). This signal is free, ubiquitous, reliable, accurate, and extremely precise. These attributes make GPS a platform for innovation.

Originally launched for military use, in the years since it was made available for private-sector use, it has enabled innovators to develop a host of applications, services, and products, increasing efficiency, productivity, and personal enjoyment. From people driving to some place new to multinational corporations coordinating complex logistics networks, hundreds of millions of users rely on GPS every day for navigation and positioning. Its precision timing capability supports industries as diverse as finance, electricity, mining, and telecommunications. Even the term *GPS* has entered the vernacular to mean one’s specific location at a specific point in time.

The focus of this analysis is on the valuation of the economic benefits of GPS since it was first made available for private-sector use [1]. GPS has been widely adopted by many industries, including 14 of the 16 industries deemed to be critical infrastructure (“Presidential Policy Directive,” 2013). Benefits were measured relative to a counterfactual in which GPS was not available and existing PNT systems and technologies continued to be used. Setting aside for the moment questions of cost, quality, and availability, where a technology alternative could have met a particular need, our valuation approach means that for that application the benefits of GPS are negligible. Where needs could not have been met, the incremental precision and accuracy provided by GPS were critical and benefits were quantified. Netting out value that could have been delivered by GPS alternatives prevents gross overestimation of benefits.

The important role GPS plays in the U.S. economy has given rise to questions about service disruptions and available alternatives. In consultation with other federal agencies, the sponsor of this work, the National Institute of Standards and Technology (NIST), in partnership with the U.S. Department of Homeland Security expanded the initial scope of this study to add an additional research question: what is the potential impact of a 30-day disruption of GPS service? A 30-day disruption seems unlikely, the impact of a disruption certainly differs on Day 1 than on Day 30, and devices capable of receiving GPS signals are also capable of acquiring signals from other GPS-like satellite constellations. However, from a policy and planning perspective, understanding the relative magnitude of potential impacts is important for making informed decisions about investments in back-up systems and contingency plans.

This analysis also charts the evolution of GPS's development, including its emergence from technologies and concepts pioneered in U.S. national laboratories and the role of different agencies and laboratories in working with different industries to take advantage of GPS's potential.

1.1 Defining positioning, navigation, and timing

The ability to measure time intervals and frequencies extremely precisely is what allows GPS users to pinpoint their location anytime, anywhere in the world. The launch of Sputnik in 1957 and the resulting space race led the United States to accelerate scientific efforts deemed essential for national security and spaceflight capability, including the creation of what is today the Defense Advanced Research Projects Agency (DARPA).

An important breakthrough occurred when U.S. researchers discovered they could discern the location of ground-receiving stations based on Sputnik's radio transmissions and accurately determine the satellite's orbit. That realization catalyzed research and development programs within the U.S. national laboratories, the military, and contractors in the private sector and academia to develop satellite systems to further American geopolitical and defense interests.

The comparison of multiple timing signals allows three general applications (see Table 1):

- Position applications leverage the ability to determine the precise location of a feature or object.

Table 1. Defining positioning, navigation, and timing (PNT)

Position	The Ability to Accurately and Precisely Determine One’s Location and Orientation Referenced to a Standard Geodetic System
Navigation	The ability to determine current and desired position (relative or absolute) and apply corrections to course, orientation, and speed at various altitudes
Timing	The ability to acquire and maintain accurate and precise time from a standard (Coordinated Universal Time, or UTC), anywhere in the world and within user-defined timeliness parameters; includes time transfer

Source(s): U.S. Department of Transportation. About PNT & Spectrum Management, available at: www.rita.dot.gov/pnt/about

- Navigation is the comparison of current to desired position and the ability to apply necessary course, altitude, and speed corrections to bring an object into a desired position.
- Timing is the ability to acquire and maintain accurate and precise time.

Although the position and navigation aspects are perhaps GPS’s best-known uses, they are enabled by GPS’s timing attribute. The timing attribute of the GPS signal is used for precision timing services by a variety of industries. For example, the telecommunications sector relies on GPS to synchronize the flow of data and voice traffic across the network, financial markets use GPS to timestamp transactions for high-frequency trading, and electric utilities use GPS to increase the efficiency of the transmission grid.

1.2 How GPS works

The current GPS infrastructure involves three segments: space, control, and user. The space segment currently consists of more than 30 satellites in multiple orbital planes. GPS satellites complete orbits every 12 hours. Each satellite contains four atomic clocks, a radio transmitter, and at least two antennas to communicate with ground control stations [Federal Aviation Administration (FAA), 2014a].

Each satellite’s transmitter broadcasts a PNT message. The message contains location, status, and a highly precise timestamp of when the message was transmitted. All GPS satellites are synchronized to Coordinated Universal Time (UTC) [2], which allows messages from different satellites to be reliably compared.

The U.S. Air Force operates and maintains the GPS system through the Global Positioning Systems Directorate, a unit within the Space and Missile Systems Center, Air Force Space Command, at Los Angeles Air Force Base. The directorate is responsible for the acquisition, development, and production of GPS satellites, ground systems, and military user equipment. In 2004, President George W. Bush directed the establishment of an interagency board to provide "guidance and implementation actions" for space-based PNT "programs, augmentations, and activities for the U.S. national and homeland security, civil, scientific, and commercial purposes" (GPS.gov, 2025). Figure 1 presents the current structure.

The control segment consists of 15 global monitoring stations, including a Master Control Station located at Schriever Air Force Base in Colorado Springs. Six monitor stations are managed by the Air Force and nine by the National Geospatial Intelligence Agency. The master control station is responsible for the overall management of the monitoring station system. The individual monitoring stations continually check the altitude, position, speed, and operational health of the satellites and feed this information to the master control station (FAA, 2014b).

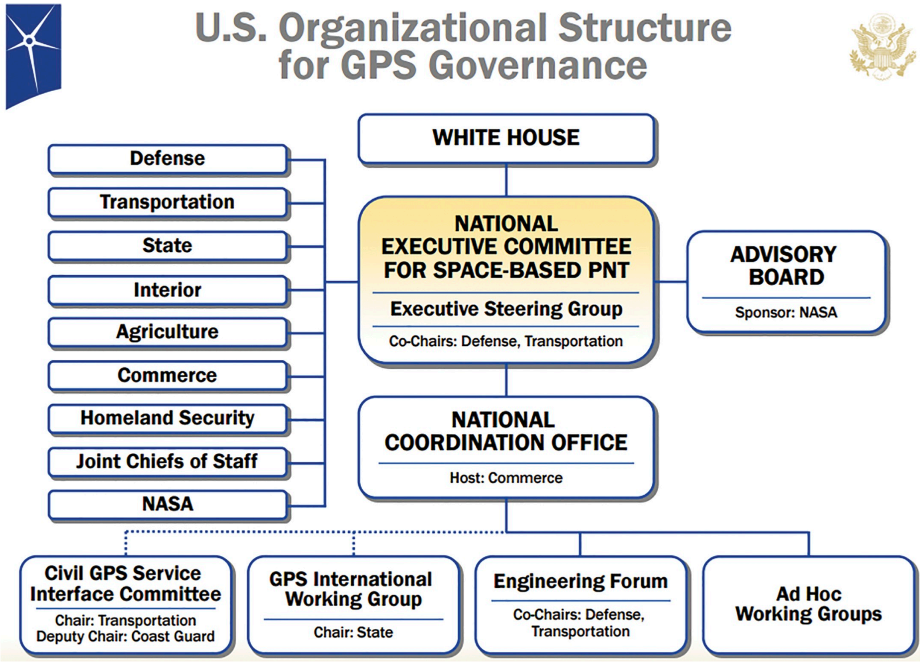

Figure 1. U.S. Organizational structure for GPS Governance
Source(s): GPS.gov. (2016d)

GPS relies on precise, synchronized time to provide accurate PNT. The U.S. Naval Observatory is tasked with maintaining the time and frequency standard for all Department of Defense (DoD) activities, including GPS [3]. A secondary master clock is located at Shriever Air Force Base. The master clocks incorporate multiple cesium atomic clocks (described later) and hydrogen masers.

The user segment consists of GPS receivers used in myriad military, government, commercial, and civilian applications. To pinpoint location, GPS receivers use messages from a minimum of four satellites [4]. By measuring and comparing the timestamps on messages from multiple satellites, the GPS receiver can determine its position in three dimensions. Basic, unassisted GPS service is accurate to roughly 8 meters 95% of the time anywhere on or near the Earth's surface. However, augmentation techniques such as Assisted GPS (A-GPS), Wide Area Augmentation Service (WAAS), and Real-Time Kinematics (RTK) can acquire greater precision from the GPS signal and improve performance in other ways.

1.3 Analysis, scope, and objectives

To better understand the value of GPS for the private sector, this analysis had three major objectives:

- Present a detailed qualitative and quantitative analysis of the retrospective economic impacts resulting from the availability of the GPS signal for use by the private sector.
- Present a detailed qualitative and quantitative analysis of the potential economic damages resulting from a 30-day GPS outage.
- Identify and characterize the federal research and technology transfer activities that supported the development and deployment of GPS.

As mentioned above, this study initially began as a retrospective analysis to estimate the economic benefits of GPS relative to other sources of position and timing information. The potential impact of a 30-day outage was later added to the scope following discussions with several federal agencies about industries' reliance on GPS and potential significant economic impacts resulting from natural disruptions (such as solar flares) or nefarious activities by bad actors. The 30-day outage period was set by this study's sponsor in consultation with other parties within the Department of Commerce.

We selected industries by determining those whose use of GPS provides them with benefits that could not have been met by other technologies or that would not have received the same level of benefits. Before GPS was made available for commercial use, the Loran system (as reviewed later in this report) delivered a signal that was readily available, if not as robust or precise. If GPS had not been made available for commercial and civilian use, Loran likely would have been expanded over time as technological advances required greater access to more precise sources of position and timing information. Thus, not only did we measure benefits relative to a counterfactual in which other technologies would have been available, but we also only included industries that developed a reliance on the incremental precision offered by GPS. Ten industries were included in this analysis.

As we review later in the methodology section, we considered several others, but it was determined that these did not have the need for the precision delivered by GPS over and above what was available from other technologies. Of course, if they are using GPS today and an outage were to occur, they could be adversely affected. A limitation from our initial scope definition means that such industries are not included. This also means that the summary results for the 30-day outage scenario should be interpreted as an underestimate of likely impacts.

Because of this limitation, the Department of Homeland Security (DHS) provided additional funding for the maritime sector to be included in our 30-day outage analysis. DHS is completing a technical assessment of GPS vulnerabilities and available back-up systems and is leveraging the results of this economic analysis. GPS's simplicity and ubiquity have led to widespread use in the maritime sector. Although the benefits of GPS relative to what mariners used to use are not great, mariners have migrated to its use. Thirty-day outage impacts could be significant. The maritime sector is an excellent example of this study's limitations. All benefits monetized and presented here may be underestimates as a consequence.

1.4 Approach overview

Our approach brought together information about the prevalence of GPS's use by industry, its adoption history, industry trends, and available alternatives. We interviewed almost 200 experts in industry, academia, and government and conducted two surveys. The first survey was fielded to surveyors with the support of the National Society of Professional Surveyors. The second was fielded to a representative sample of American smartphone users to understand the extent to which they rely on their phones' location services for emergency services, navigation, games, check-ins, and other activities.

Although other studies have quantified impacts associated with GPS, they either were specific to an application (e.g., precision agriculture; Schimmelpfennig, 2016), or they were generalizations that relied on desk research to assess impacts (e.g., Leveson, 2015; Pham, 2011). Note that we do not assess the geopolitical and national defense value of GPS. Our scope was civilian and commercial use, with an emphasis on the role GPS plays in meeting private-sector needs for precision PNT information.

We present the results for each industry as a separate case study. How GPS adds value differs by industry, as does the method used to quantify that value. Providing a case study for each industry ensures that each industry's use was appropriately contextualized and described.

1.5 Organization of the monograph

This monograph is organized as follows. In Section 2, we provide an overview of GPS and the history of innovation in the national laboratories that led to the its development. In Section 3, we present an overview of our methodology that complements the industry-specific approaches detailed within each case study. In Section 4, we overview the 10 industries and sectors listed in Table 2 and describe economic impacts. In Section 5 we summarize impacts and reflect on the implications of this work.

Table 2. Industry sector coverage

Sector	Specific Analytical Focus
Agriculture	Precision agriculture technologies and practices
Electricity	Electrical system reliability and efficiency
Finance	High-frequency trading
Location-based services	Smartphone apps and consumer devices that use location services to deliver services and experiences
Mining	Efficiency gains, cost reductions, and increased accuracy
Maritime	Navigation, port operations, and recreational boating
Oil and gas	Positioning for offshore drilling and exploration
Surveying	Productivity gains, cost reductions, and increased accuracy in surveying
Telecommunications	Improved reliability and bandwidth utilization for wireless networks
Telematics	Efficiency gains, cost reductions, and environmental benefits through improved vehicle dispatch and navigation

2. The history of GPS technology

The technology comprising today's GPS has progressed through multiple technology life cycles over the past 60 years [5]. Military objectives drove the initial development of space-based navigation systems, and as such, the national laboratories with Department of Defense (DoD) support took the lead role in research and development of enabling technologies. For example, research at the Naval Research Laboratory (NRL) and Air Force Research Laboratory (AFRL) established satellite orbital planes, discovered passive ranging techniques to account for signal delays, and performed R&D and testing procedures for critical equipment designed for space travel. Multiple early systems saw the underlying technologies and infrastructure be developed and proven, moving capabilities from two-dimensional (latitude and longitude) to three-dimensional (adding altitude) positioning. In 1973, NAVSTAR integrated existing programs to produce the more accurate and robust system in use today.

The network of technology developers ultimately included the labs, government agencies, research universities, and private-sector contractors. Once selective availability was turned off in the mid-1990s, the private sector took the lead in developing the technologies needed for most of today's commercial applications, building on the base of technology from earlier years. The timeline in Table 3 illustrates how research objectives and the roles of government and industry have evolved over time.

This section describes how today's GPS system evolved from national laboratory technologies and programs. Our focus is on noting key programs and milestones; many comprehensive histories of GPS's development exist. For reference, Table 4 presents a timeline of significant milestones.

Table 3. U.S. Satellite navigation systems, programs, and manufacturers

Program	Owner	Years active	Key technology capabilities
Vanguard	U.S. Navy	1955-1959	Used solar cells to power radio transmitter, collected novel information about satellite orbits as well as geophysical characteristics of Earth
Transit	U.S. Navy	1959-1996	Established orbital patterns and predictions
System 621B	U.S. Air Force	1963-1973	Developed “pseudo-random noise” signal to resist jamming
Timation	U.S. Navy	1964-1973	Developed passive-ranging technique using high-stability clocks and time reference for positioning
NAVSTAR GPS	U.S. Air Force, JPO	1973-present	Installed atomic clocks onboard GPS satellites; delivered civil and military signal; ground, control, and space segments maintain timing integrity

(*continued*)

Table 3. Continued

GPS satellite block	Manufacturer	Launch period	Key technology capabilities/improvements
GPS Satellite Block	Manufacturer	Launch Period	Key Technology Capabilities/Improvements
I	Rockwell International (Boeing)	1978-1985	Design life of 5 years, two L-band navigation signals, served as concept testing series
II	Rockwell International (Boeing)	1989-1990	Nuclear detection sensors, designed to operate for 14 days without contact from control segment
IIA	Rockwell International (Boeing)	1990-1997	Durability improvements, designed to operate for 180 days without contact from control segment; 7.5-year design lifespan
IIR	Lockheed Martin	1997-2004	Replacement satellites for Block II, 7.5-year design lifespan
IIR-M	Lockheed Martin	2005-2009	Included military signal (M-code) and new civil signal (L2C), 7.5-year design lifespan
IIF	Boeing	2010-2011	Included third civil signal (L5), inertial navigation systems, 12-year design lifespan
IIIA	Lockheed Martin	2014 onwards	Include a fourth civil signal (L1C), higher broadcasting power, navigation enhancements, improved interoperability, greater jamming resistance, 15-year design lifespan

Source(s): Whitlock and McCaskill (2009), Pace (1995), GPS.gov. (2017b)

Table 4. Notable milestones in the development of GPS

Year	Achievement
1954	The utility of space-based satellites is in review by various scientific agencies; a study is proposed to NSF
1955	DoD recommends the Naval Research Laboratory Scientific Satellite Program—which became Project Vanguard
1957	Soviet Union launches Sputnik I and II satellites
	Attempt to launch Project Vanguard's first satellite (TV3) is unsuccessful
1958	United States launches first satellite into orbit—Explorer 1—under the direction of the Army Ballistic Missile Agency
	Project Vanguard successfully launches Vanguard 1 satellite
1959	Transit satellite navigation system developed at Johns Hopkins Applied Physics Laboratory
1963	System 621B, a navigation system developed by Air Force, is established
1964	Timation is established by the Naval Research Laboratory and led by Roger Easton
1968	DoD establishes steering committee—NAVSEG (Navigation Satellite Executive Steering Group)—to coordinate satellite navigation efforts
1973	In April, DoD further pushes for coordination, naming the Air Force to lead a new initiative called the Defense Navigation Satellite System (DNSS). DNSS was overseen by the Joint Program Office (JPO). NRL is still involved
	In December, the NAVSTAR GPS concept is approved by the Defense System Acquisition and Review Council (DSARC)
	Phase 1 of the GPS program begins; intended to confirm the concept of space-based navigation
1974	First NAVSTAR satellite—Navigation Technology Satellite (NTS)—is launched. It was a refurbished Timation satellite built by the NRL. It used the first atomic clock in space—a rubidium atomic standard
	NRL expands cesium clock development for use on future satellites
1977	NTS-2 satellite is launched carrying first cesium atomic clock into space

(*continued*)

Table 4. Continued

Year	Achievement
1978	First of 11 Block I satellites launched between 1978 and 1985
1983	After a Korean plane was accidentally shot down by the Soviet Union, President Reagan announces his intentions to make GPS available to civilian aircraft for free when the system is operational
1989	The U.S. Coast Guard assumes responsibility as the lead agency for the Civil GPS Service within the Department of Transportation The first five GPS Block II satellites are launched; From 1989 to 1997, 28 satellites are launched, including the last 19 being updated versions (Block IIA)
1991	First combat use of GPS is used in the Persian Gulf War, enabling U.S. military forces to validate its usefulness in the featureless Iraqi desert
1994	GPS is announced as operational and integrated into the U.S. air traffic control system FAA announces implementation of the WAAS to improve GPS integrity and availability for civil users in all phases of flight
1996	Transit satellite system ceases operation on December 31 at 2359 GMT
2001-2003	Combat following 9/11 attacks and during Operation Iraqi Freedom further demonstrates the precision of GPS in military conflict
2005	First “modernized” GPS satellite is launched (IIR-M) that transmits a second civilian signal for enhanced performance
2008	U.S. Air Force announces award to Lockheed Martin for the development and production of GPS III satellites
2010	Russian GLONASS system completes constellation of 24 satellites, becomes fully operational U.S. Air Force announces award to Raytheon to development next-generation Operation Control System (OCX)
2012	BeiDou reaches regional Asia-Pacific coverage
2016	The EU’s Galileo achieves Early Operational Capability with 18 satellites in orbit

Source(s): Pace (1995), Whitlock and McCaskill (2009), GPS World (2014)

2.1 Project vanguard

The International Geophysical Year (IGY)—from July 1957 to December 1958—was an international cooperative engagement to study the geophysical properties of Earth. The Naval Research Laboratory established Project Vanguard in 1955 to represent the United States in the IGY. On December 6, 1957, Project Vanguard's first satellite launch failed, resulting in a near-immediate explosion at Cape Canaveral, Florida. The failed launch, dubbed "Flopnik," was carrying Satellite TV3 (Test Vehicle 3), the purpose of which was to conduct an orbital analysis and collect other information on the environmental (radiation) effects on TV3. Four months later, Project Vanguard successfully launched a replacement satellite into orbit. The following year, Vanguard 1—the first solar-powered satellite in space—was successfully launched. Vanguard 1 ultimately met the project's goals by collecting valuable information on Earth's physical, atmospheric, and environmental properties. Project Vanguard ended with the launch of Vanguard 3 in 1959.

2.2 Transit

Transit was initially developed to accurately provide navigation data for Polaris missile submarines and other ships at the ocean surface. After the unexpected launch of Sputnik 1, researchers studied the satellite's radio signals and eventually could determine the satellite's location in orbit (Guier and Weiffenbach, 1998). This research contributed to Transit's development in 1958 through a joint effort between DARPA and Johns Hopkins Applied Physics Laboratory (Aerospace Corporation, 2010). After a failed satellite (Transit 1A) launch in 1959, the second attempt in launching a Transit satellite (Transit 1B) was successful. In 1964, the system was transitioned to the Naval Research Laboratory.

By 1968, Transit was fully operational with 36 satellites in orbit. Transit operated for 28 years until 1996, when the Defense Department replaced it with the current GPS system. Transit was initially designed to provide accuracy within about 0.5 nautical miles (926 meters) but eventually reached a level of accuracy of 0.1 nautical miles (185 meters) (Transit—US Navy Navigation Satellite System, 2025). The system was two dimensional and thus did not measure altitude.

Transit was significant in proving space-based navigation was possible and provided technical contributions to later navigation systems through the orbits and orbital prediction methods.

2.3 System 621B

System 621B originated at the Aerospace Corporation and was supported by the U.S. Air Force. It was the first satellite navigation system to feature three-dimensional navigation, which was needed to monitor aircraft positioning ("Evolving Solutions," n.d.). Another contribution of 621B was that it used a signal called pseudo-random noise to resist jamming. The signal was tested on aircraft between 1968 and 1971 and was ultimately verified in 1972 at White Sands Proving Ground in New Mexico (Stanford, 1995). System 621B's signal structure and frequency were ultimately used in the first iteration of GPS (Pace, 1995).

2.4 Timation

Timation (short for Time and Navigation) was a program developed by the Naval Research Laboratory in 1964. This program was instrumental in the history of navigation systems because of its emphasis on precision time references to provide accurate positioning. Although atomic clocks were not yet employed in satellites, Timation satellites used high-stability clocks that were regularly updated and synchronized with a master clock on the ground (Beard *et al.*, 1986). The program proved three-dimensional navigation (latitude, longitude, and altitude) was possible through its "passive ranging" technique. The U.S. Naval Observatory was also involved in developing the timing equipment used in Timation satellites and was active in research toward atomic time standards.

The Timation program launched only two satellites—in 1967 and 1969—but was instrumental in the use of time references to pinpoint locations on Earth ("Navigation Technology Satellites," n.d.). In 1973, the program merged with System 621B, and its third satellite (Timation III) was redesigned under the new NAVSTAR program and launched in 1974.

2.5 Atomic clock development

The most accurate clocks rely on some source of frequency. The frequency needs to have an oscillation period that is well characterized, resistant to external disrupters, and highly stable (Lombardi *et al.*, 2007). Mechanical clocks used pendulums that swung at relatively constant rates to measure time to within up to one-hundredth of a second per day. In 1927, a breakthrough in time keeping was developed using the frequency provided by quartz crystals. The quartz clock's accuracy exceeded the pendulum-driven clocks because of the piezoelectric properties of the crystal, which vibrates at a precise frequency when jolted with electricity. Quartz clocks are still abundantly available today in watches, clocks, and appliances. This concept of frequency remains true even in the most advanced clocks.

The development of advanced atomic clocks by NIST (then called the National Bureau of Standards [NBS]) and the UK’s National Physical Laboratory provided one of the most critical technology components of satellite navigation. In 1949, the NBS built the world’s first atomic clock using ammonium absorption. However, this clock was primarily experimental and was never used for practical purposes. “Atomic,” in more recent terms, refers to the use of measuring the electron frequency of an atom—cesium or rubidium, most commonly—for timekeeping. In 1955, researchers at the National Physical Laboratory in the UK built the first cesium atomic clock. Although early research was performed at national laboratories, private companies innovated and improved the atomic clock for practical purposes, such as space-compatible clocks to be launched aboard satellites.

In 1974, the first atomic clock (NTS-1) was launched aboard a GPS satellite. This was followed by continued research to improve timing standards and develop a series of new atomic clocks, which were incorporated into the GPS system as it evolved. Table 5 presents the noteworthy timeline of atomic clock development.

The atomic clock has become perhaps the most critical technology component of satellite navigation because of the level of precision required. The signals sent and received by satellites, ground stations, and GPS receivers rely on coordinated time standards so that accurate positioning is maintained. If there is lack of timing coordination or if timing standards were less accurate by some orders of magnitude, then the positioning errors of meters to hundreds of meters could likely result. Given that four satellites need to be simultaneously visible to provide location information, it is critical that timing and signal delivery from satellite to ground-based clocks and receivers are synchronized to support today’s applications (Piester *et al.*, 2011).

The Time and Frequency Division at NIST, through Defense Advanced Research Projects Agency (DARPA) funding and collaboration, developed the chip-scale atomic clock (CSAC), which is now being developed and marketed by private companies. Weighing just 35 grams and consuming 115 mW of power, the CSACs enable portable applications for military and commercial uses (Fetter, 2013). For military uses, the CSAC’s low size, weight, and power consumption complement other gear required in the field such as improvised explosive device jammers. Its highly accurate timing synchronization also helps to prevent self-jamming and can track GPS signals more quickly and with less visibility (i.e., a minimum of three satellites in view

Table 5. Notable milestones in precision timing

Year	Achievement
1949	World's first atomic clock is built by NIST (then the NBS)—it used ammonia absorption
1951	Cesium atomic beam device is completed at NBS with Office of Naval Research funding
1952	First atomic clock using cesium atoms for frequency is built by NIST, named NBS-1, although not accurate enough to be a time standard
1955	• Louis Essen at the UK's National Physical Laboratory built the first atomic clock accurate enough to be a time standard • ONR contracts the National Company, Malden, Massachusetts, to produce a military atomic clock based on that of Jerrold R. Zacharias of MIT, with engineering characteristics set forward by the Navy Bureaus of Ships and Aeronautics and the Naval Research Laboratory
1956	The National Company produces Atomichron, the first commercial cesium atomic beam clock
1958	Commercial cesium clocks become available, costing $20,000 each, developed by The National Company
1959	NBS-1 becomes NIST's primary frequency standard
1960	First atomic hydrogen maser (or frequency standard) was built at Harvard. NBS-2 is developed at NIST's laboratories in Boulder, Colorado
1963	NBS-3 is developed and offers improved accuracy and stability
1964	Cesium atomic beam tubes are developed by Varian Associates for Hewlett Packard
1967	The 13th General Conference on Weights and Measures defines the second as the vibrations of the cesium atom, which replaced astronomical timekeeping
1968	NBS-4 is developed as the world's most stable clock, used into the 1990s as part of the NIST time system
1972	NBS-5 is developed and serves as the new primary standard
1975	NBS-6 is developed; it is accurate to within 1 second in 300,000 years
1993	NIST-7 is developed and is 20 times more accurate than NBS-6
1999	NIST-F1 begins operation—it is accurate to 1 second in 20 million years
2014	NIST launched NIST-F2, an atomic clock accurate to 1 second in 300 million years

Source(s): Pace (1995), Whitlock and McCaskill (2009), Bhaskar *et al.* (1996), Lombardi (2012) versus the normal four). Unmanned aerial vehicles also benefit from CSAC's small physical properties as well as its ability to improve signal detection and jamming resistance (Symmetricom SA.45s CSAC, 2016).

Since the Unites States' primary civilian time and frequency standard, NIST-F2, was initiated in 2014, NIST researchers have already been developing significantly more precise atomic clocks. Although the Naval Observatory oversees GPS time, NIST manages civilian timing applications, and its R&D activities contribute to GPS timing and frequency standards in the future. In 2015, the strontium lattice atomic clock demonstrated that it would "neither lose nor a gain one second in some 15 billion years." For comparison, this level of performance is 50 times more precise than the NIST-F2 cesium fountain atomic clock. An example of the strontium atomic clock's practical application is measuring gravitational shift based on marginal changes in altitude—as marginal as 2 centimeters (National Institute of Standards and Technology, 2016). Additional research at NIST has combined two experimental atomic clocks based on the frequency of ytterbium atoms. The double clock has further increased precision and stability by eliminating a distortion in laser frequency that synchronizes that atoms (NIST, 2016a). Like the potential new applications and discoveries made possible through the strontium atomic clock, the double clock could improve the current performance of PNT as well as enable new capabilities.

2.6 NAVSTAR GPS

With Navy and Air Force satellite-based navigation programs advancing in parallel and limited by the availability of resources, the DoD designated that the existing systems be consolidated into one comprehensive system led by the Air Force (Pace, 1995). In December 1973, the Joint Program Office (JPO) approved the concept of NAVSTAR (Navigation System with Timing And Ranging) GPS and incorporated the best features of Transit, Timation, and System 621B (Rip and Hasik, 2002).

The new GPS system launched its first satellite in July 1974, designated Navigation Technology Satellite 1 (NTS-1), which was a refurbished Timation satellite. NTS-1 carried the first atomic clock into orbit—a rubidium frequency standard. The second (and last) of the NTS series carried the first cesium atomic clock into space (Pace, 1995).

GPS was originally planned as a constellation of 24 satellites, which were to be launched in phases, or "Blocks." Eleven Block I satellites—launched between 1978 and 1985—were launched as the initial developmental satellites to establish feasibility (Global Positioning System, n.d.). The Block II satellites were designed and launched to establish operational capacity. The first Block II satellite was launched in February 1989 and featured significant improvements over the Block Is including radiation-hardened electronics, selective availability and anti-spoofing capabilities, and automatic error detection for certain conditions (Pace, 1995). Between 1989 and 1996, 27 Block II and Block IIA (Advanced) satellites were launched. Figure 2 presents the number and timeline of GPS satellite launches by Block. All satellites launched before 1996 are now retired.

GPS provides two levels of service that operate on different frequencies: (1) the PPS frequency restricted to U.S. Armed Forces, federal agencies, and selected allied armed forces and governments and (2) the SPS available for civil and commercial use (NASA, 2012).

The first military test of GPS was carried out during Operation Desert Storm during the Persian Gulf War in 1990. In the vast expanse of the Iraqi desert, military personnel used GPS to navigate the featureless terrain (Space and Missile Systems Center and SMC History Office, 2016). Their weapons' precision and movement capabilities were considered crucial to success in the conflict. Not only did GPS prove to be valuable for military purposes, it began to be used in humanitarian operations, such as delivering relief supplies through air drops.

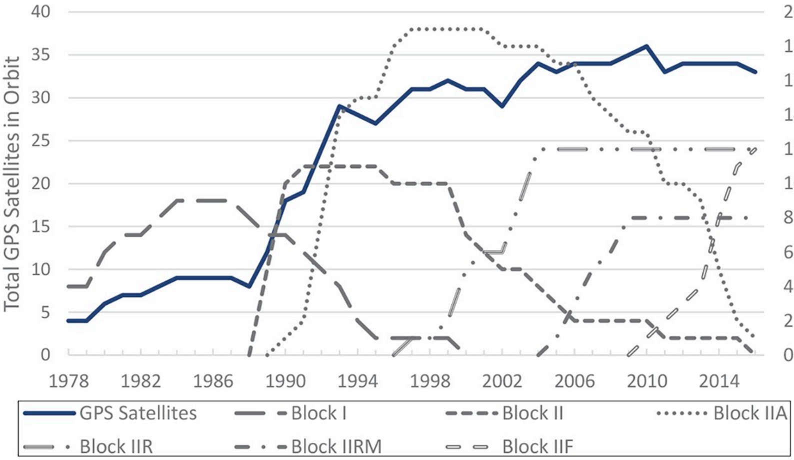

Figure 2. Timeline of GPS Satellites in Orbit
Source(s): GPS World (2016)

In 1996, President Clinton made good on President Reagan’s promise to make GPS available for civilian use at no cost after Korean Air Lines Flight 007 was shot down in 1983 after flying too close to Soviet airspace (BBC News, 1983). The system’s availability for civilian use sparked new industry segments and applications. Select availability was turned off in 2000.

3. Methodology overview

The methodology for valuing the economic benefits of GPS's provision of spaced-based positioning, navigation, and timing (PNT) signals will be specific to each industry sector included in the study. This methodology overview discusses our general approach, common assumptions, and areas of overlap. Then, each sector has a stand-alone case study with methodological notes specific to the valuation of the benefits GPS delivers to it.

To reiterate a point made in the introduction, our goal is not to value PNT services themselves, but to value PNT as it is delivered by the GPS system. This framing allows us to consider other PNT delivery systems as potential alternatives to GPS when developing counterfactual scenarios for benefits estimation. When GPS became available, a variety of delivery systems were in place that provided PNT services, including NIST time, Loran-C, and OMEGA.

3.1 Conceptual approach to valuing economics benefits

The economic assessment characterizes the benefits of GPS by how it improves production methods, improves product attributes, or both. To illustrate these distinctions, consider the following three technology examples:

1. Improved production: A mining company uses GPS positioning to increase the efficiency of its transportation and hauling activities. The process now produces an identical commodity at a lower cost.
2. Improved product: The telecommunications industry uses GPS precision timing to synchronize its towers. This reduces/eliminates dropped calls and

increases the bandwidth, enabling more advanced networks such as 4G LTE and 5G.

(3) Both improved: The electricity industry uses GPS frequency to synchronize its phase measurement units, which in turn reduce transmission and distribution losses (improved production of electricity) and increase system reliability (improved product).

Figure 3 provides a simple graphical depiction of the three scenarios, illustrating how the market impacts of these technology innovations differ. In the first example, production costs have lowered, shifting the supply (marginal cost) curve to the right. In the second example, the net benefit to consumers is now greater, shifting the demand curve to the right. In the final example, both curves have shifted to the right: we refer to this sort of technological innovation as a "market-spanning" innovation; it changes both the supply and demand curves in the market.

Each of the three chosen examples increases total welfare, measured by the area above the supply curve and below the demand curve. Thus, conceptually the benefit of GPS is measured by the incremental welfare area generated by the shift in the curves.

The graphs in Figure 3 illustrate improvements in production and/or in quality for an existing product or service. For example, prior to GPS the United States had a highly functional electricity system serving all customers. GPS then lowered the cost and increased the quality of electricity service.

However, in some instances, it can be claimed that certain products or services would not be possible or would not have been developed without GPS. For example, most of the location-based apps popular with consumers today would not exist without the free and ubiquitous precision location capabilities provided by GPS. In this

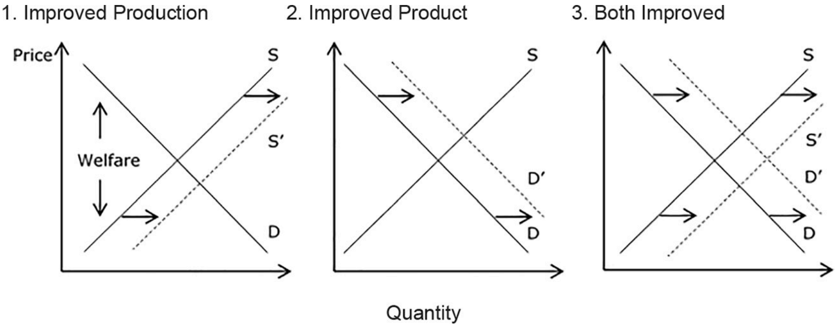

Figure 3. Three scenarios of consumer and producer surplus expansion

instance, the entire welfare triangle above the supply curve and below the demand curve can be attributed to GPS.

As we have already noted, the exact method for quantifying the benefits of GPS will be different for each sector and may also differ for specific products and services within a given sector. Thus, each sector section will have its own economic benefits methodology section.

3.2 Counterfactual A: in the absence of the availability of GPS for civilian use

Economic impacts are measured relative to a counterfactual scenario that describes what otherwise would have been in place or would have occurred in the absence of the technology being analyzed. For this study, developing a counterfactual means answering two key questions:

(1) What did each sector of interest use before GPS was available (if anything)?

(2) In the absence of GPS, are there other technologies that would have evolved or been invented to provide some of the same services that GPS provides?

To answer these questions, we conducted research and scoping interviews with sector-specific GPS experts to understand the technology landscape in the late 1980s and early 1990s when the private sector first began leveraging GPS for commercial applications. In general, the feedback was that some industries (e.g., agriculture) would have continued using the same technologies for their PNT needs that had been used before GPS was available. Other sectors (e.g., telecom) were actively exploring alternative technologies at the time when GPS was adopted; both scenarios provide insight into what technologies might otherwise have been used in the absence of GPS.

One such alternative technology is Loran-C, a land-based PNT system that was originally developed for marine navigation purposes (Justice *et al.*, 1993). Additionally, as recently as the 2000s, both government and the private sector were researching and testing an enhanced Loran system known as eLoran, although it was never made operational. Both Loran-C and eLoran provide the same kind of timing and frequency signal as GPS, but in most cases, Loran is less accurate and precise (see Table 6). Additionally, the evolution of Loran-C into eLoran over time would have been different from GPS, potentially affecting the development of some commercial applications.

For most of the sectors, our counterfactual assumption is that in the absence of GPS a Loran-based network (similar to Loran-C) likely would have received more

Table 6. Precision and accuracy performance of Loran-C, eLoran, and GPS

	Loran-C	eLoran	GPS
Frequency	1×10^{-11} Frequency Stability	1×10^{-11} Frequency Stability	1×10^{-13} Frequency Stability
Timing	100 ns	10-50 ns	10 ns
Positioning (meters)[a]	18-90 m	8-20 m	1.6-4 m

Note(s): [a] The positioning accuracy of each of these technologies varies widely by type of receiver and augmentations being applied. The accuracy quoted here for GPS is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard

Source(s): Narins *et al.* (2012), Curry (2014), Celano *et al.* (2003), www.gps.gov/

investment to fully cover the U.S. This would have been used for many of the same applications that rely on GPS today. Note that it is possible that many applications across several sectors would be able to leverage a Loran-C signal to achieve the same benefits that are experienced using GPS today, effectively eliminating the benefits of GPS for those applications under this counterfactual scenario.

3.3 *Counterfactual B: an unexpected 30-day outage of the GPS system*

Under a 30-day outage of GPS scenario, we assumed that neither Loran-C nor eLoran would be available as a backup. Neither one of these systems is operating today, nor could these systems be implemented within the 30-day time window of our analysis. We also assumed that other international global navigation satellite systems (GNSSs), such as GLONASS or Galileo, would also not be available for use within the 30-day time window.

Hence, the counterfactual for the 30-day failure of GPS is simply the quality/reliability of each sector's current backup system. These systems include backup timing systems and the associated level of holdover these clocks/systems may have. For most positioning applications, the location-based GPS functionality would not be possible at all, forcing the sectors to revert to pre-GPS alternative processes.

3.4 *Approach for selecting industry sectors*

Because of the vast and growing number of applications reliant on GPS, the study needed to down select to the key sectors whose use comprises the bulk of the economic benefits. Our approach to selecting sectors was based on the following criteria:

1. *Need for precision*: For both position and timing, the level of precision needed for the GPS application for the industry/sector was ranked as high, medium, or low as follows:
    - Position:
        - High: less than +/− 1 meter
        - Medium: +/− 1 meter to 10 meters
        - Low: greater than +/− 10 meters
    - Timing:
        - High: less than +/− 1 microsecond
        - Medium: +/− 1 meter to 1,000 microseconds
        - Low: greater than +/− 1 millisecond
2. *Alternatives*: In the absence of GPS, are there technology, behavioral, or process options available to achieve the associated function?
    - Yes: Alternatives to GPS are available. They might be less efficient, but the industry/sector would not be dramatically affected.
    - No: The function or application that GPS enables would not be possible.
    - Costly: Alternatives are available but at significantly higher cost or loss of efficiency/functionality.
3. *Scale*: What is the size of the industry or market for the GPS applications?
    - Large: Large industry/application size with significant market penetration.
    - Medium: Either industry/application size or market penetration is modest.
    - Small: Both industry/application size or market penetration are modest/small.

Table 7 summarizes the assessment of the criteria for the industries with significant GPS applications. This table was based on an assessment and review of available literature, and in some instances individual ranking (high, medium, low) were changed based on further research and scoping interviews.

We finalized the key industries to be included in the detailed analysis and present the methodology for quantifying economic impacts along with detailed counterfactuals for each selected industry. Based on our assessment and discussions with industry and government agencies, the following focus sectors were selected:

- agriculture;
- electricity;
- financial services;

Table 7. Summary of precision need, alternatives and application scale by industry sector

Industry/Sector	Need for precision position	Need for precision timing	Alternatives to GPS	Potential scale of impacts
Aviation	Low	Medium	Yes	Medium
Maritime transportation	Medium		Yes	Large
Rail transportation	High		No	Medium
Road navigation/telematics	Medium		Yes	Large
Agriculture	High-Medium		No	Large
Conservation	Low		Yes	Small
Forestry	Low		Yes	Small
Surveying	High		Costly	Large
Public safety and disaster relief	Low		Yes	Medium
Mining	Medium		Yes	Medium
Oil and gas sector	Medium		Yes	Medium
Electricity sector		High	Costly	Large
Construction and mining	Medium—low		Yes	Large
Space	Medium		No	Small
Finance		Low	Yes	Large
Telecommunications		High	Costly	Large

- location-based services;
- maritime;
- mining;
- oil and gas;
- surveying;
- telecommunications; and
- telematics.

3.5 *Approach for quantifying economic benefits by sector*

Because of the variety of sectors included in the analysis, we employed several different methods to estimate the benefits delivered by GPS. These valuation approaches can generally be grouped into the following categories:

- Changes in production costs: Additional labor, capital, materials, or energy is needed to produce the same product or service. For example, GPS improves vehicle fleet management and logistics, reducing fuel cost and increasing utilization of the existing fleet.

- Changes in productivity and/or revenue: For example, precision agriculture increases crop yield which can be valued at market prices.
- Willingness to pay (WTP): WTP is a stated preference approach where individuals or businesses are asked to value a service, activity, or product attribute. For example, what are consumers willing to pay for location-based services/apps via their smart phones.

Table 8 shows the valuation approach we employed for each sector. In almost all sectors GPS helps lower production costs high levels of precision at very low costs. In some sectors GPS enables totally new products and services and can be valued by increased revenue. If it is likely that new services are generating significant consumer surplus above market price, a willingness to pay approach is used. Some sectors (such as maritime) used multiple approaches to value different benefits in different

Table 8. Summary of benefits valuation approach by sector

Sector	Changes in production costs	Changes in productivity and/or revenue	Willingness pay
Agriculture	X	X	
Surveying	X		
Telematics	X		
Location-based services			X
Mining	X		
Oil and gas	X	X	
Telecommunications			X
Electricity	X	X	
Financial services	X		
Maritime	X	X	X

subsectors (commercial fishing: lost revenue, recreational boating: WTP, navigation in seaways: increased operating costs). Details on individual valuation approaches are provided in each sector section.

All dollar values are presented in real, 2017 terms except where noted.

4. Industries and sectors

4.1 Telecommunications sector

The telecommunications industry relies on continuous, error-free information transfer across a large country and a myriad of independent network operators, all of which requires sophisticated synchronization systems. Today, this synchronization is predominantly accomplished by leveraging precision time and frequency signals from GPS. GPS functions as a common source of synchronization for the entire industry.

Because it was critical to unlocking advanced wireless networks with the implementation of 4G LTE, we estimate the economic impact of GPS to range from $81 billion (based on firms' willingness to pay for spectrum) to $686 billion (based on consumers' willingness to pay for increased bandwidth and speeds). During a 30-day outage of GPS, we estimate the economic loss would range from $5.5 billion to $14.2 billion.

Although telecom network operators have used other sources of precision time and frequency in the past and still use atomic clocks extensively, the network infrastructure has evolved to rely heavily on GPS. GPS is a free, ubiquitous signal that can be captured with relatively inexpensive equipment from anywhere in the world—something that cannot be said for any other source of precision timing.

As the demand for ever more sophisticated and high-performance telecom services has grown, the technology has evolved around GPS. This is especially true in wireless networks, which often do not have access to a precision timing signal from the wireline network. Although other technologies exist to meet the needs of network providers, none are widely implemented or available. The result is a critical infrastructure (telecommunications) that is heavily reliant on a single source of precision timing.

Precision timing enables a number of telecom services, including the synchronization of traffic between carrier networks and across wide geographic areas, initializing calls between wireless handsets, wireless handoff between base stations, carrier aggregation, directional antennas and adaptive transmission power control, and billing management. On wireless networks, higher levels of precision timing enable service providers to increase bandwidth and handle more devices within the same infrastructure and wireless spectrum as technology evolves. Table 9 details the level of precision timing required for both wireline and wireless networks by standard-setting bodies, including the International Telecommunications Union (ITU), the European Telecommunications Standards Institute (ETSI), and the Alliance for Telecommunications Industry Solutions (ATIS) [6].

Table 9. Timing precision requirements in telecommunications

Application	Precision needed
Wireline (sources of timing)	
PRTC (primary reference time clock)	± 100 ns with respect to Coordinated Universal Time (UTC)
ePRTC (enhanced primary reference time clock)	± 30 ns with respect to UTC
Wireless	
CDMA2000	± 3-10 μs
TD-SCDMA	± 3 μs
WCDMA-TDD (NodeB TDD mode)	± 2.5 μs
W-CDMA MBSFN	± 12.8 μs
LTE MBSFN	< ± 1 μs (spec. still under study)
W-CDMA (Home NodeB TDD mode)	Microsecond-level accuracy
WiMax	± 1-1.43 μs
LTE-TDD (wide area base station)	3 μs (small cell, < 3 km radius) 10 μs (large cell, > 3 km radius)
LTE-TDD (home area base station)	3 μs (small cell, < 500 m radius)
LTE-TDD to CDMA handovers	± 10 μs
IP network delay monitoring	± 100 μs to ± 1 ms

Source(s): Adapted from ATIS (2017)

Precision requirements characterized in Table 9 reflect the requirements of the most advanced wireless technology available today. Previous generations of telecom infrastructure did not require as much precision. However, even in the late 1980s, wireline networks required at least microsecond-level accuracy to maintain reliable synchronization across a wide geographic area (Butterline *et al.*, 1988).

In addition to using receiver equipment to directly access a time signal from GPS, telecom service providers also distribute time over their terrestrial fiber networks using Precision Time Protocol (PTP), which measures the delay between network points to calculate an accurate timing signal. However, while PTP theoretically could be used to distribute time independent of GPS, it typically synchronizes to UTC using GPS, so it does not function as a suitable alternative to GPS in its current implementation. Similarly, telecom network operators use atomic clocks on wireline infrastructure, but the clocks are typically disciplined using GPS.

4.2 Precision agriculture

The agricultural sector uses the precision location information provided by GPS to improve agricultural mechanization and efficiency. In agriculture, efficiency refers to the ability to produce more food, feed, and fiber per unit of labor and other inputs (e.g., seeds, chemicals).

Precision agriculture, abbreviated as PA in this case study, is a concept that refers to the ability for farmers to conduct site-specific management—to observe, measure, and respond more precisely to inter- and intrafield variability in crops. Before GPS was available for commercial use, farmers had few technologies that allowed them to proactively manage their fields according to the fields' spatial characteristics. GPS played an essential role in the advent and continued adoption of PA technologies and methods. The retrospective impact of GPS, net of adoption costs, is conservatively about $5.8 billion.

If GPS were not available for civilian use, farmers would have continued managing their operations as before, planting and harvesting as they have done historically without the benefit of automated steering or the ability to make decisions based on site-specific information. This counterfactual is not entirely speculative; many farmers today do not use GPS and still farm this way. An alternative system with less accuracy, such as eLoran, could have helped farmers take advantage of some PA technologies such as aerial spraying, coarse yield and soil mapping, or certain kinds of variable-rate technologies (e.g., applying fertilizer to more precisely meet site-specific crop needs), but without GPS these would have been less effective and provided fewer benefits. These technologies would also likely have taken longer to develop.

The proportion of farmers using PA technologies has increased steadily over the last three decades, and these technologies are now used on the majority of U.S. farmland. In the event of a 30-day failure of GPS today, there would be a significant planting delay and adverse impact on yields for many farmers, especially the large, mechanized farmers that have fully embraced PA. Many tractors, combines, and other equipment have GPS technologies integrated into their systems. These farmers would face a steep learning curve and significant efficiency losses trying to either retrofit or operate this equipment without GPS, or they would return to earlier ways of applying inputs.

The impacts would be highly dependent on the time of year, with the largest impacts expected during planting seasons. We estimate that in a worst-case scenario the economic loss would be more than $15 billion if it occurred during the planting season.

GPA-assisted PA technologies allow farmers to manage inputs such as seeds, agrochemicals, and fuel more efficiently, increase yields, and reduce farmworker fatigue and errors. The three most common categories of these technologies are yield and soil mapping, machinery guidance and control systems, and variable-rate technologies (see Table 10):

- *GPS-assisted yield and soil mapping* quantifies and maps information pertaining to yield and/or soil variability throughout a field. Farmers can use this information along with other farm-specific information (e.g., soil, climate, pests) to diagnose issues within the field and respond proactively.
- *GPS-assisted machinery guidance and control systems* automatically steer farm equipment in a predetermined path to help farmers reduce overlaps or skips or have built-in input control valves to avoid applying inputs where they are not needed (e.g., headlands). Aerial spraying, or crop dusting, is another GPS-assisted technology that has transformed the way that agrochemicals are applied to agricultural fields.
- *GPS-assisted variable-rate technologies* enable farmers to vary the timing and rate at which they apply inputs such as seeds and agrochemicals to more precisely meet their crops' needs.

Table 10. Three most common categories of GPS-enabled precision agriculture technologies

Application	Precision needed	Co-Technologies	Benefits: Qualitative description	Counterfactual	Technical impact metric	Economic value metric	Potential magnitude of impacts
Yield and soil mapping	10 m	GPS + combine yield monitor GPS + soil sampling data GPS + mapping software	Helps farmers more intensively manage their fields; allows farmers to make more informed planting and input application decisions, including how much and where to apply agrochemicals, plant seeds, and irrigate	Collecting yield data using sensors and without mapping or mapping using alternatives to GPS.	Changes in crop yield, input costs (e.g., seeds, fertilizer), and overhead costs (e.g., labor, capital). Environmental benefits include reductions in greenhouse gas (GHG) emissions and nutrient loads in waterways.	Additional net returns on adoption vs. nonadoption on area where the technology was applied. Value of ecosystem services from applying less agrochemicals.	Medium
Tractor and combine guidance system	5 cm–1 m depending on use	GPS + navigation tool (e.g., parallel swathing)	Allows farmers to more precisely apply inputs and harvest crops while reducing overlap and/or skips within a field. Also reduces machine operator error, operator time, operator fatigue, and multitasking	Manual steering of tractors and combines. Apply inputs manually based on markers such as a mechanical marker on a planter or harvester or foam marker on a sprayer.	Changes in crop yield, input costs (e.g., seeds, fertilizer), and overhead costs (e.g., labor, capital). Environmental benefits include reductions in GHG emissions and nutrient loads in waterways.	Value of additional net returns on adoption vs. nonadoption area. Value of ecosystem services from applying less agrochemicals.	Medium
Variable-rate technology	10 cm–1 m depending on use	GPS + variable-rate planter drive GPS + variablerate spreader drive GPS + variablerate applicator	Allows farmers to apply inputs (e.g., seeds, agrochemicals) at predetermined rates at different locations in a farmer’s field	Adjust inputs manually or apply at one rate throughout the field.	Changes in crop yield, input costs (e.g., seeds, fertilizer), and overhead costs (e.g., labor, capital). Environmental benefits include reductions in GHG emissions and nutrient loads in waterways.	Additional net returns on adoption vs. nonadoption on area where the technology was applied. Value of ecosystem services from applying less agrochemicals.	Medium

Many different technologies fall into one of these three broad categories. These categories are also not mutually exclusive; farmers also frequently employ these techniques in combination with each other.

PA in large-scale farming in the United States became possible when the NAVSTAR GPS system became available for civilian use in the early 1990s. The development of the first PA technologies preceded the civilian availability of GPS, but they were limited to small field boundaries marked with posts or flags. For a short time before GPS, radar positioning systems were used as location devices for agricultural applications (mostly for research), but the systems were cumbersome and needed radar posts to function (Tillett, 1991).

When GPS became available for civilian use, there were some limits to its precision. Fortunately, differential GPS (DGPS) was introduced in the late 1990s, which improved location accuracy, thereby paving the way for increased precision in agrochemical application and enabling automated steering in farm vehicles. Because some applications require higher precision than others (Table 14), DGPS became essential to the widespread adoption of PA.

The annual PA dealership surveys of crop input dealers, sponsored by *CropLife* and Purdue University, detail the current state and trends of the industry (Erickson *et al.*, 2017). Retailers expect their market areas to expand for all PA uses; they expect some categories of technologies to expand more than others including variable-rate technologies and some new and emerging GPS-enabled technologies such as unmanned aerial vehicles, satellite or imagery, and data storage and analysis.

4.3 Electricity sector

The electricity sector uses the precision timing provided by GPS to synchronize electrical waves in the power grid and detect potential problems and faults in the transmission infrastructure. GPS has been a key factor in making phasor measurement units (PMUs) cost-effective and pervasive in the United States' electricity infrastructure.

In the absence of GPS, the electric utility system would likely have continued to rely on its existing supervisory control and data acquisition (SCADA) systems. However, the use of PMUs enabled by GPS has led to a slight (1 to 2%) decrease in the probability and duration of outages and enhanced generation testing/modeling, resulting in economic benefits of approximately $15.7 billion since 2010.

In the event of a 30-day outage of GPS today, a major disruption of the electrical system is unlikely because of safeguards and contingency plans in place. However, the probability of outages might increase. In addition, faults occurring from natural or non-natural events would take longer to identify and repair, increasing the duration of outages. The economic loss is estimated to be approximately $274.8 million from a 30-day GPS outage with little to no physical damage to the system.

Electricity suppliers can use the precision timing provided by GPS to monitor the daily operations of the power grid down to the nanosecond. This monitoring is conducted by PMUs, which evaluate electrical waves to detect potential problems and faults in the power distribution infrastructure. To realize this real-time monitoring and analysis, a large number of synchronized PMUs, or synchrophasors, are linked to a common time source that enables them to time stamp the dynamics of the electrical system. The time source is the Coordinated Universal Time (UTC), which is provided via the GPS system (Coppolino *et al.*, 2011).

Historically, power systems using SCADA have depended on its *relative time* clock features to perform daily monitoring operations. Relative time refers to the timing of triggering events such as a fault or lightning strike relative to their starting points; that is, the zero point is precisely when the event in question occurred (North America Synchrophasor Initiative (NASPI, 2012). This timing capability allows for SCADA's scan time (frequency of data collection) to range between 1 to 2 seconds and 10 seconds or more (NASPI, 2012). These time scans work well for localized events on small decentralized systems, such as a single generating source supplying a stand-alone grid system. However, they do not work well across a wide-scale interconnected grid system. For many years, it was recognized that the power system data captured by different SCADA systems could be far more valuable if the systems all used a common time standard to "time tag" their measurements.

Beginning in the late 2000s, GPS-based PMUs began to be installed in the electrical system to augment the SCADA-based systems for state estimation. Because PMUs collect data at a much higher sampling rate than SCADA systems, the granularity of the data helps reveal new information about dynamic stability events on the grid.

By 2015, the installed number of PMUs reached approximately 1,800, offering nearly 100% coverage of the transmission system (NASPI, 2012).

Synchrophasor technology uses *absolute time* to gauge the state of the system. This timing approach both time-synchronizes and time-stamps data against UTC, or local time, available through GPS (NASPI, 2012). As a result, synchrophasors make possible the monitoring of the electrical grid at 30 to 120 time-tagged samples per second, approximately 100 times faster than SCADA (NASPI, 2012). When data will be used to provide automatic control actions, it is imperative that timing remains as accurate, secure, and reliable as possible (NASPI, 2012). Given that these data must possess an absolute time precision of 1 μs (NASPI, 2012), highly accurate monitoring of the power line dynamics in real time is only attainable by using GPS UTC time stamps.

Today's wide-area grid is highly interconnected. PMUs using GPS have helped make this possible while maintaining resilience. For example, analyses of event observations have shown that during a generator trip situation, frequency is reduced in a proportional way. This reduction, monitored in a certain point, quickly spreads across the transmission lines, thereby showing up in other sites with a certain delay. But with the propagating generator trips evaluation feature of the synchrophasors, the exact location of the event and the power trip misbalancing can be identified, and necessary countermeasures can be subsequently taken. This characteristic allows for the forecasting of serious events such as blackouts and readies the remote power supplier with storage energy sources (Coppolino *et al.*, 2011).

Table 11 summarizes the precision timing needs and applications for the electricity sector. Applications range from precision timing needs in the nanoseconds for traveling-wave fault detection milliseconds to less demanding uses. Event reconstruction and system time/frequency are the applications with the greatest precision timing needs.

The precision timing needs for different applications drive the benefits associated with GPS. For example, time-of-use billing requires time stamps, but the level of precision is minimal. In contrast, fault detection requires extremely accurate time stamps because electricity flows at close to the speed of light.

4.4 Financial services sector

The financial services sector uses GPS to time stamp financial transactions. GPS's timing capability allows exchanges and trading houses to cost-effectively time stamp every transaction request received in keeping with the precision required by financial regulations.

However, experts who specialize in the intersection between precision timing and financial services note that a number of alternatives to GPS meet or could have met the precision timing requirements specified by U.S. Securities and Exchange Commission (SEC) regulations and industry standards. Alternatives include a system of networked atomic clocks, network time protocol (NTP), or Loran.

Table 11. Electricity sector precision timing uses and needs

Application	Precision needed	Benefits: qualitative description	Counterfactual	Technical impact metric	Economic value metric	Potential magnitude of impacts
Event reconstruction	1 ms	Accurate time tags greatly speed up event reconstruction, helping to prevent future events	Manual time stamping and longer event reconstruction time	Frequency, magnitude, and duration of blackouts	Economic impact of outages	High
Phasor measurements	5-6 μs	Monitors grid instability and increases grid efficiency	Less efficient grid system	More efficient dispatch and reduced transmission losses	Fuel and increased capacity requirements	High
System time and frequency	5-50 ms	Line frequency is used by end users as a time standard (clocks in appliances)	Less accurate clocks. Not an issue for appliances but impact other apps	Increased cost for some applications needing time standards		Low
Billing and power quality incentives	50 ms: Billing 1 ms: Power quality harmonics	Customers typically monitor themselves, and utility bill estimates need to match; thus, accurate time is key	Less reliable M&V for harmonics incentive programs	Impacts due to incentive program (partial attribution)	Value of load shifting and improved power quality	Low
Traveling-wave fault detection	0.1 μs	More precisely locate the point of fault	Longer ground-based search time	Speed time to identifying and fixing faults on large transmission lines (300-500 M spans)	Value of reducing the duration of the outage	High

GPS was adopted because the signal was ubiquitous, convenient, and inexpensive to acquire. The high level of timing precision (5 to 10 ns) was not the driving factor for adoption. As such, it is unlikely that there would have been any delay in notable industry advances, such as high-frequency trading (HFT) if GPS has not been available. Retrospective economic impacts associated with GPS for the financial services sector, relative to available alternatives, are estimated to be negligible.

In the event of a 30-day GPS outage, financial markets would need to adjust, but operations would be minimally affected. Most exchanges and sizable trading houses have rubidium or cesium clocks that can provide sufficient holdover to continue operations. Although the financial services sector views the falsification of GPS signals, or spoofing, as a significant concern because it can affect data reliability, sector representatives do not view an observable loss of GPS for 30 days as having a substantial economic impact.

The growth in the use of GPS in the financial services sector is linked to the precision-timing regulatory requirements. A main driver of the precision timing has been HFT.

HFT uses statistical algorithms to place and execute large amounts of stock orders within extremely short time intervals. Although the profit per transaction from HFT is often small, at high volumes the approach can yield significant revenue. As of 2012, automated transactions initiated by co-located servers accounted for 50 to 70% of the trading volumes on the U.S.’s major exchanges (Humphreys, 2012).

Throughout the growth of HFT, its use has been controversial. Despite its efficiencies, HFT increases the chances of fraud in the stock market. Larger, faster traders could have advantage over smaller, slower traders (Lombardi, 2015). The difference in size and speed usually translates into much larger trade volumes that could drive up stock prices. This situation creates an incentive to prioritize the transactions of large investors, thereby increasing the likelihood of fraudulent activities. For example, illegal activities known as “front running,” in which the transactions of larger and generally faster traders are prioritized over those from small investors to drive up prices and where trading order can be manipulated, become increasingly possible if trades are time stamped by a clock with a resolution of only 1 second or greater (Lombardi *et al.*, 2016). As a result, HFT has been a driving force behind regulations that increase trading time-stamp precision.

Fraudulent activities related to HFT have occurred. A 1996 SEC report concluded that the National Association of Securities Dealers (NASD) and NASDAQ did not consistently operate under their customers’ best interests because unchecked collusion was present among market makers and trades were not correctly executed. In an attempt to remedy this situation, NASD issued several rules, numbered as 6950 through 6957 (SEC, 2006) aimed at improving market surveillance and overall operations, including time-stamp precision. Rule 6953, entitled "Synchronization of Member Business Clocks," required all computer systems and clocks on NASDAQ to be synchronized to within 3 seconds of the NIST atomic clock before daily operations begin every business day (Lombardi *et al.*, 2016). This rule took effect in 1998, and the enforcement of identical time requirements spread to the New York Stock Exchange through the adoption of Rule 132A in 2003. Although the 3-second synchronization requirement prompted financial markets to stop using decimal clocks and any other types of clocks unable to display seconds, it was still considered to be somewhat coarse (Lombardi *et al.*, 2016).

In 2008, after NASD had been merged with other entities to form the Financial Industry Regulatory Authority (FINRA), the Order Audit Trail System Rule 7430 required all stock market clocks in the United States to be synchronized to within 1 second of NIST time (Lombardi, 2015). This was done to continue minimizing the probability of fraud.

FINRA Regulatory Notice 14-47, implemented in February 20, 2017, further decreased the synchronization requirement for stock market transactions to 50 milliseconds. However, this is still a relatively modest regulatory requirement when compared with the nanosecond level of precision provided by GPS.

In the financial services sector, precision timing has two main uses: time synchronization and latency. Time synchronization makes it possible to determine with a high degree of accuracy the order in which trades and transactions are executed. Latency capabilities deal with the travel times of transactions between two venues located at two different geographic points. GPS enables the fast realization of lengthy measurements, which reduces the time it takes for two or more market participants at different locations to interact with one another.

In addition to helping avoid the front-running issues referenced earlier, synchronization and latency capabilities help exchanges and participants improve their level of coordination, allow for better and more accurate real-time analyses, and meet SEC regulatory requirements. From a regulatory point of view, it is important to have time stamps precise enough to discern causal relationships from one venue to another and any other cause-and-effect relationships between market centers. Assessing this relationship is highly dependent on the geographic distance between the centers. The travel time from one financial location to another typically ranges from 100 to 200 microseconds. Therefore, the timing needed to discern the sequence in which orders are executed must be within or below 100 microseconds. GPS easily enables time stamps with such precision, providing a direct reference to UTC's authoritative source of day-to-day time.

In the event of the loss of GPS reception, most exchanges and trading houses have backup systems to ensure time-stamp accuracy and avoid sending incorrect data with potential time errors. These systems often include a rubidium clock capable of maintaining relatively accurate time should a temporary failure of GPS occur. When GPS is temporarily disrupted, these rubidium clocks are prepared to "run free," or undisciplined, to maintain the correct time. Using these clocks is also referred to as going into "holdover" mode. In the short term, the frequency stability between UTC and undisciplined rubidium clocks is virtually the same. However, the undisciplined rubidium clocks start drifting after about 1,000 seconds and will deteriorate to approximately 1 microsecond synchronization after several days (Lombardi *et al.*, 2016). As described in the following section, this level of drift would likely not affect trading over a 30-day GPS outage.

Table 12 presents the main trading applications that require time stamps and the level of precision needed in terms of maximum divergence from UTC. For example, HFT requires the highest level of precision at 100 microseconds. Other trading activities typically require significantly less precision.

Although HFT represents the majority of transactions, it is by no means the only transaction mode used. Voice transactions are still widely used in the daily operations of financial exchanges. The role of voice communications in the market is important given that institutional investors still execute "single-stock" trades, also known as "high-touch" channel trades, via telephone. Financial products such as "swaps" are considered to be more complex, reason why their transactions are still conducted via telephone by a large number of trading professionals (Groenfeldt, 2016). For these types of transactions, reliable time stamping is important, but the required level of precision is low.

Another financial mechanism requiring time stamping is the request for quote (RFQ), a type of procurement solicitation whereby companies ask outside vendors to offer a quote to help them complete a task, such as purchasing a sizable amount of a specific product (Titton *et al.*, 2016). Given that an RFQ focuses mostly on pricing and many bidders may provide different price quotes at different times, correctly recording the specific time at which the bids are made is necessary. In a similar vein, when

Table 12. Finance sector precision timing uses and needs

Type of trading activity	Maximum divergence from UTC	Benefits: qualitative description	Counterfactual	Technical impact metric	Economic value metric	Potential magnitude of impacts
HFT	100 μs	It enables stock exchanges to handle many thousands of trades within a 1-second interval	Dedicated precision timing system (atomic clocks) for financial services sector	Bid/ask spread was down to 3 points in 2014 (from 90 points 20 years before)	Economic value of HFT (in terms of liquidity and arbitrage)	High
Voice trading	1 s	Primarily used to confirm order receipts, discuss current and future market conditions, trade performance, and allocation instructions	NIST time/broadcast	No impact on trading activities	Cost of non-GPS timing system	Low
Request for quote system	1 s	Provides the bidder with important information about the requirements of a specific task or project	NIST time/broadcast	No impact on trading activities	Cost of non-GPS timing system	Low
Negotiated transaction	1 s	Companies can buy or sell assets and other companies	NIST time/broadcast	No impact on trading activities	Cost of non-GPS timing system	Low

Source(s): Gopalakrishnan (2016)

companies undertake negotiated transactions to purchase and sell or when auction processes between buyers and seller take place, reliable time stamping is required.

However, again, for all of these non-HFT trading activities, the level of precision required is only around 1 second.

4.5 Location-based services

GPS chips in smartphones and other consumer devices receive satellite signals and generate precision location information that software applications use to deliver services and experiences to users. Apps help users navigate, learn what or who is nearby, track location in real time, check in and interact, play games, and enjoy experiences tailored to their geographic position (Spiekermann, 2004; Ryschka *et al.*, 2016). There is a public safety component as well. Enhanced 911 (E911) automatically provides a caller's location to 911 dispatchers, shortening response times for emergency assistance.

The location information needed for location-based services (LBS) to operate is obtained from a combination of GPS, Wi-Fi hotspot, and cell towers. However, GPS is often the most critical of these. LBS would be far less precise without GPS, which could undermine some applications' utility. For example, without GPS, navigation systems could not accurately track a driver's position and deliver live turn-by-turn directions [7]. Similarly, E911 would be limited to less precise cell tower triangulation only.

In this case study, we quantify the benefits GPS-enabled LBS generate for users (e.g., driving times reduced by turn-by-turn directions) and society (e.g., air pollution reduced by shorter driving times). We estimate that GPS-enabled location services for smartphones and consumer devices generated about $218 billion in private and public benefits between 2007, the first year for which we could reliably calculate benefits, and 2017. Under the forward-looking assessment of a 30-day outage, we estimate that losses would total $2.9 billion.

Our estimates are likely conservative estimates because data limitations meant that we were unable to monetize all social benefits. For example, because turn-by-turn directions also reduce the number of miles driven, there may be fewer automobile accidents. Emergency services may arrive earlier because of E911. Although we could not monetize benefits such as these, we discuss many qualitatively.

For the purposes of this study, we considered three types of LBS:

- **Navigation services** refer to navigation devices and smartphone applications that provide users with turn-by-turn driving directions and real-time alerts on road conditions.

- **Non-navigation smartphone applications** refer to applications that use location information to enhance social networking, gaming, local search, and advertising.
- **Emergency services** refer to emergency calls from cell phones to be located more accurately through services like E911. GPS also allows survivors to be more accurately located and damage mapped during natural disasters.

After GPS was first made available for civilian use, except for personal GPS receivers, the few consumer applications of GPS technology that were available were found in luxury items [8]. Further development of LBS occurred after the E911 mandate was passed in 1996. This mandate required mobile network operators to be able to locate emergency callers on mobile phones within a certain degree of accuracy. Most network operators did not have this capability and had to make significant investments to meet the mandate. To generate additional returns, many network operators searched for commercial applications of location technology (Bellavista *et al.*, 2008). Early LBS applications consisted of "finder services," which would upon request return lists of nearby points of interest. Unfortunately, these generated little consumer demand and were phased out soon afterward.

Cell phones and in-car portable devices became popularly available between 1999 and 2001. The first mobile phone with a GPS component, the Benefon Esc!, became available in 1999 (Sullivan, 2012). Around the same time, companies like Garmin and TomTom began offering personal in-car navigation devices that provided turn-by-turn directions.

In the early 2000s, several advances reignited LBS development. Qualcomm developed "assisted GPS," or AGPS technology, which combined GPS signals with cellular signals to provide accurate location to users within a few feet (Hampton, 2016). Other key advances included those in chip processing power, miniaturization, memory, graphical interfaces, and 3G wireless broadband. These technologies laid the foundation for LBS for personal devices.

Providers began offering services for fleet management (covered in the Telematics sector), as well as child and pet trackers. Apps that initially used less accurate and reliable cell tower triangulation switched to GPS. Some users, with GPS-capable phones and spreading location technology, began writing simple applications that shared their location data with other users. Many of these early initiatives grew into successful businesses in gaming, health, and marketing.

The first iPhone was released in 2007, kicking off production of smartphones with built-in GPS components and providing a platform for location-based apps. Smartphone ownership by American adults has increased from 35% in 2011 (the first year for which data are available) to 77% in January 2017. In January 2017, 92% of 18- to 29-year-olds owned a smartphone (Pew Research Center, 2018).

Apps like Google Maps, Yelp, and Foursquare brought LBS to the mainstream. In 2011, approximately half of smartphone owners reported having ever used GPS for directions (Zickuhr and Smith, 2011); by 2012, about three quarters of smartphone owners said they had used LBS on their phones at least once (Zickuhr, 2012).

By 2015, 95%, 94%, and 82% of U.S. adults aged 18 to 29, 30 to 49, and 50 or older, respectively, reported having used their phones to get directions, recommendations, or other information related to their location (Anderson, 2016). Consumers' willingness to use these services has also grown: in 2013, 35% of smartphone users reported intentionally turning off the location features on their phone (Zickuhr, 2012), but by 2016, 90% of users left them on (Kaplan, 2016).

Beyond smartphones, the market for portable navigation devices was and anticipated to grow at about a compound annual growth rate (CAGR) of 15% by 2020 (TechNavio, 2016). The automotive navigation market is also valued at $11.3 billion in 2016 and anticipated to grow at a CAGR of 8% by 2025 (Inkwood Research, 2016).

LBS are now integrated into the everyday lives of millions of consumers. They can be a valuable part of one's entire day, from locating car keys in the morning, checking traffic and choosing a faster route to work, to looking up a nearby restaurant for lunch and reading its reviews, getting a geofenced reminder to complete an errand after leaving the office, tracking the route taken on a run, and finding a nearby date (Ryschka *et al.*, 2016).

4.6 *Maritime industries*

GPS is used pervasively in commercial shipping, fishing, and recreational boating for navigation and tracking. GPS is the primary means of navigation for nearly all vessels. This case study focuses on GPS' use in the maritime sector, what would have been used for navigation and port operations if GPS had not been made available, and alternatives should there be a GPS outage [9].

For the purposes of this analysis, we have divided the maritime sector into five subsectors:

(1) commercial fishing;
(2) recreational fishing and boating;
(3) port operations;
(4) navigation in seaways; and
(5) passenger transport including cruise lines.

We find that although GPS is pervasive throughout the maritime sector, if it had not been made available, the sector would have most likely continued to use Loran-C or similar technologies with minimal impact on operations or economic output. The accuracy provided by Loran-C is sufficient, and in the absence of GPS most electronic navigation systems would have evolved using this alternative. Thus, we do not quantify retrospective benefits.

In contrast, because currently there is no backup for GPS, an unexpected outage of GPS today would have significant economic impacts. We estimate a 30-day outage of GPS to have an impact ranging from \$7.8 to \$14.6 billion, with a point estimate of \$10.4 billion. The largest impacts are associated with interruptions in port operations and the resulting economic impact of supply chain disruptions. The range of impacts associated with the 30-day outage analysis reflects the fact that there is some uncertainty regarding the extent to which subsectors in the maritime industry (primarily ports) could respond and adapt over the 30-day GPS outage time period to mitigate impacts.

The maritime sector uses GPS for precision positioning and navigation and as an enabling technology of the Automatic Identification System (AIS), the Global Marine Distress and Safety System (GMDSS), and Vessel Monitoring Systems (VMS). GPS is the primary means of navigation for nearly all vessels except for smaller recreational boats.

GPS acts as an enabling technology for several technologies in the maritime sectors. The following technologies are either entirely dependent on GPS or use GPS for some functions and would operate in a diminished capacity in the absence of GPS. Some of these technologies are widely used and are present across many of the subsectors analyzed in this report [10]. Others are specific to a single subsector and are discussed in greater detail later in the report.

Gyrocompasses, or gyroscopic compasses, are nonmagnetic compasses that use a spinning gyroscope and the Earth's rotation to find true north and use GPS for calibration. Finding true north is more navigationally useful than finding magnetic north. Unlike traditional compasses, gyrocompasses are unaffected by ferromagnetic materials, such as steel. These characteristics make gyrocompasses particularly well suited for use on ships. As such, they are widely used and are the preeminent means of finding geographic direction.

Gyrocompasses are subject to “steaming” errors due to rapid course changes. These errors cause the gyrocompass north to be deflected east or west depending on the direction of travel. Modern gyrocompasses rely on GPS input to correct these errors.

GPS acts as an enabling technology of AIS. AIS is a shipboard broadcast system that acts like a transponder designed to be capable of providing information about the ship to other ships and to coastal authorities automatically (U.S. Coast Guard, 2018b; International Maritime Organization [IMO], 2019a). This information includes dynamic information such as position, speed, heading, and rate of turn as well as static information such as call sign, name, vessel type, and destination (MarineTraffic, 2025). AIS is required under the IMO’s International Convention for the Safety of Life at Sea (SOLAS) for all passenger ships, tankers, and other ships over 300 gross tons. AIS is primarily used in ship reporting, navigation, and collision avoidance.

ECDIS is a geographic information system that replaces paper navigation charts. It displays geographic information from electronic navigational charts [11] or digital nautical charts [12] and overlays position information from GPS and other navigational sensors. Additionally, ECDIS integrates with radar, AIS, depth sounders, and Navtex and overlays data from these systems on the electronic chart. ECDIS is a useful tool for mariners because it displays information from several systems in a single location. ECDIS is not required by IMO or U.S. Coast Guard regulations but is approved as a replacement for nautical charts and is widely used.

A VMS consists of a National Marine Fisheries Service (NMFS)–approved transmitter that “$\ldots$ automatically determines a vessel’s position and transmits that position to an NMFS-approved communications service provider. The communications service provider receives the transmission and relays it to NMFS” (National Oceanic and Atmospheric Administration, 2025). GPS is the primary means of providing position data for VMS. VMS is used by environmental groups and NMFS to monitor and enforce compliance with fisheries regulations. VMS is required on commercial fishing vessels operating in some U.S. fisheries. Fishing vessel operators working in these fisheries are required to declare their catches via electronic logs that are transmitted through VMS.

PPUs consist of a combination of sensors, a laptop, and software that assists pilots in safely navigating a ship into a port. These sensors are independent of the piloted ship's sensors. PPUs use several sensors including gyroscopes, inertial sensors, and GPS receivers. These sensors provide essential data to the pilot such as the roll and pitch of a vessel, speed, position, and heading. The use of pilots is compulsory in most ports, and most pilots use PPUs.

GMDSS is "an integrated communications system using satellite and terrestrial radiocommunication systems" (IMO, 2019b). GMDSS is required under the IMO's SOLAS regulations for vessels over 300 gross tonnage on international voyages and all passenger ships. In the case of an emergency, GMDSS alerts search and rescue organizations such as the U.S. Coast Guard. Additionally, it alerts nearby vessels that may be able to offer assistance. The system relies on GPS to provide the vessel's position to rescue authorities.

Digital communications systems that use time division multiplexing use the GPS signal for timing corrections. Maritime vessels use a combination of analog radios in the UHF and VHF bands and digital communications such as satellite radios.

4.7 Surface mining

The mining sector relies on precision positioning signals provided by GPS to explore and identify promising ore bodies and support mine-site construction, extraction, and hauling processes. GPS also has been a key technology for making mines more productive and safer by reducing collisions and reducing the number of workers who are exposed to dangerous situations.

Analysis indicates that if GPS were not available for civilian use, the U.S. mining sector would have relied on a suite of technology alternatives that may have afforded some but not all of GPS's advantages. We estimate that for mines that have fully adopted GPS-enabled technologies, the gross productivity gains are 12.5% per year (measured as cost reductions holding output constant). Net productivity gains from GPS compared with a counterfactual without satellite-based positioning are 9.4% per year. We estimate cumulative net productivity benefits of $12.3 billion for the U.S. mining sector since 1990.

In the event of a 30-day outage of GPS, it is likely that there would be substantial short-term disruption to mines relying on GPS. Mines tend not to have backup systems for GPS-enabled technologies and would need to fall back on work practices that were in place before precision positioning. Most mines, and especially larger ones, would likely contract with additional workers to meet their immediate needs in areas such as real-time surveying. Fleet management would also be harder to optimize without GPS which would result in more idle time of haulage trucks and machines [13]. We estimate that production during the 30-day disruption could decline in the short term by 24%. The direct economic loss from a 30-day outage would be approximately $950 million.

GPS positioning is used widely in resource extraction. We focus on open pit surface mines, which rely heavily on GPS-enabled technologies and applications across the mine life cycle, from initially mapping ore deposits to designing and building mines to operations. Because GPS signals are generally limited to line of sight and cannot be received reliably underground, underground mines have accrued limited benefits [14]. Therefore, we exclude underground mining, and when we refer to “mining,” we mean the surface mining portion of the mining sector unless otherwise noted.

U.S. mines produced an estimated $75 billion of raw materials in 2017 (U.S. Geological Survey, 2018). Although production statistics are not disaggregated for surface mines, as of 2015, 12,637 active surface mining operations across the United States employed 194,000 workers (Centers for Disease Control and Prevention [CDC] National Institute for Occupational Safety and Health [NIOSH], 2015), which is about 82% of total mine workers [15].

Companies in the mining sector rely on GPS extensively for a wide range of applications including

- exploration and surveying;
- construction;
- extraction;
- optimization of fleets within the mine site; and
- outbound logistics.

Mines use GPS to increase the precision of operations and reduce labor costs. Increasing precision and reducing labor costs increase overall productivity, which means that GPS allows companies to hit similar levels of production with fewer input costs.

According to experts in the use of GPS for mining, the greatest uptake has been in industry segments that have greater profit margins. For example, large precious metal mines in the western United States such as the Bingham Canyon copper mine run by Rio Tinto [16] would be a likely place to find GPS ingrained in all aspects of operations. However, we learned that companies in the aggregates industry (e.g., construction materials) have been less likely to invest in GPS, which is the result of their smaller size and narrower profit margins. Additionally, mines that are owned by major parent companies that can amortize capital investment costs over larger levels of production and reach greater economies of scale have tended to invest more in GPS-enabled technologies and human capital.

4.8 GPS in the oil and gas industries

GPS is used extensively in exploration and production (E&P) operations in the oil and gas sector. It has improved productivity, reduced labor requirements, and enhanced safety. It has also permitted oil and gas companies to drill wells in deeper water further from shore. In the absence of GPS, terrestrial operations would likely have employed a combination of radio-based navigation systems, cellular navigation systems, pseudolites, and traditional surveying and mapping techniques. Offshore operations closer to shore likely would have relied on similar technologies. However, GPS alternatives do not offer the range or precision required for deepwater operations.

We estimate that GPS has improved gross productivity by 32% for companies that use GPS technology in offshore oil and gas exploration and drilling. Relative to Loran, the incremental productivity gain for GPS is 17% [17]. Using data from expert interviews and secondary sources, we estimate that GPS has generated cumulative cost savings of $45.9 billion from 1990-2017 for offshore oil and gas operations. These cost savings have accrued for both nearshore and deepwater oil and gas operations.

In the event of an unexpected outage of GPS, offshore exploration, development, and construction operations would likely be disrupted. A GPS outage would negatively impact dynamic positioning systems for vessels, resupply efforts, and drilling operations. Production in shallow water would continue with minimal disruption, but production in deepwater would experience significant disruption. The production of existing fixed rigs would not be affected by a GPS outage. Floating rigs, on the other hand, rely on GPS for dynamic positioning during production. Therefore, production of these rigs would be affected by an outage. An outage could also negatively affect the ability to replenish the crews and supplies of both fixed and floating offshore rigs. New drilling operations that rely on GPS could also be affected. We estimate that offshore production would decrease by 41%, and future construction and development operations would be delayed during the outage. This loss would amount to a short-term output loss of about $1.5 billion.

The oil and gas sector is an important component of the U.S. economy with $326 billion in total output in 2017 (BEA, 2018). Its operations can be divided into three segments: upstream operations, midstream operations, and downstream operations (PSAC, 2019). Upstream operations, also known as the E&P sector, involve determining the location of oil and gas through exploration and extraction by drilling wells. Midstream operations consist of processing, storage, marketing, and transportation of crude oil and natural gas. Downstream operations include the refinement of oil and the production of petrochemical products and the distribution of natural gas, fuel, and petrochemical products to retail outlets.

Of these segments, upstream operations are the most reliant upon GPS, especially offshore operations, which is the focus of this case study [18]. As of 2017, offshore operations account for about 18% of crude oil and 5% of natural gas production (EIA, 2017). The share of oil production occurring offshore declined sharply from 2010 to 2014 and has remained fairly stable over from 2014 to 2017. The share of natural gas production occurring offshore has been declining since 2002. Long run-projections from the EIA indicate that the offshore share of production for natural gas and oil are expected to decline to 3% and 12%, respectively, by 2050.

4.9 Professional surveying

The surveying industry was one of the earliest adopters of GPS, and it continues to use precision location information to improve the productivity and lower the costs of surveying tasks. Surveyors are experts at precisely measuring spatial characteristics and were one of the first professions to understand the potential of GPS and to apply it to their work. Surveying applications are critical to many disparate but economically important sectors, such as construction, land registration, mapping, mining, and infrastructure planning.

Before GPS was available, surveyors used technologies that were effective at achieving high levels of accuracy, but with higher labor costs, longer time frames, and lower productivity levels. Given the sub-cm level accuracy required by surveyors and the high accuracy levels that traditional technologies can achieve, if GPS had not been developed or had not been available it is unlikely that an alternative such as eLoran [19] would have been able to achieve the high-resolution accuracy required by surveyors. With no viable alternative, we estimate that GPS has provided the surveying industry with $48.1 billion of benefits since 1984, and an average of about $2.7 billion per year since 2010.

If GPS became unavailable for 30 days, the surveying industry and the broader economy would experience immediate consequences because most surveyors perform

GPS-assisted surveying and rely on the productivity enhancements that it provides. Surveyors would need to switch to more traditional techniques and tools, which would cause delays, higher costs, and productivity losses for surveying activities. Economic sectors that rely on surveying would also be delayed. We estimate the total cost of a 30-day GPS outage to the surveying industry to be $331 million.

The U.S. Bureau of Labor Statistics (2018) recorded 43,430 people in the United States employed as surveyors in May 2017 [20], and accounted for approximately $7.2 billion [21] in revenue. The majority worked in architectural, engineering, and related services, with others in local and state governments and infrastructure construction industries. The industry is characterized by small-scale operators.

Surveyors have widely adopted GPS and incorporated it broadly into surveying techniques; almost all surveyors use GPS in at least some of their work or rely on GPS by accessing geodetic networks [22]. Using geometric calculations and technology, surveying has broad applications in construction, architecture, urban planning, engineering, archaeology, real estate, mining, agriculture, and other industries that rely on accurately identifying and mapping boundaries and land features.

GPS brought immense benefits to the surveying field. According to the surveying experts interviewed for this study, GPS enables surveyors to greatly enhance their productivity, compared with traditional surveying. Surveyors can reliably complete more jobs with similar accuracy levels in less time and with less labor.

Traditional surveying methods require a “line of sight” between the topographic points being measured, meaning at least two workers are required to measure points no further apart than can be seen and have no visual obstructions between the points. With GPS, this requirement is eliminated, freeing surveyors to measure distant points that may have obstacles between them. Thus, surveying companies can field smaller teams to do often larger jobs. This fact was one of the big selling points when GPS was introduced to the surveying industry and remains one of the primary benefits today.

Surveying is also one of the sectors that requires the highest levels of accuracy, often less than 1 cm and sometimes even less than 1 mm, depending on the application. While traditional surveying methods can achieve this accuracy, GPS enables surveyors to obtain similar levels of accuracy in less time. In the GPS receiver market, the receivers with the highest accuracy are called “survey grade” to indicate that they can be used for survey purposes.

However, GPS does have some drawbacks. GPS does not always provide improved accuracy over other techniques, especially in situations with interference in the line of sight between receivers on the ground and satellites in the sky (Kizil *et al.*, 2006;

DiBiase, 2025). In heavily forested areas, dense urban locations, or over very short distances, surveyors may use a conventional method rather than GPS. Also, by eliminating the need to survey several points using line of sight, there is also the unintended consequence of sometimes losing the additional geographic detail in between those points.

Surveyors typically use a combination of old and new techniques in their work. Older technologies that are still used today in the United States include the “total station,” or “robotic total station,” an improved electronic version of a traditional technology called a theodolite (a surveying instrument with a rotating telescope for measuring horizontal and vertical angles). Differential GPS is typically used for surveying applications in the form of real-time kinematic (RTK) [23] observations with permanent base stations. This technology provides the accuracy required for most survey applications.

Few comprehensive reviews of the economic benefits of GPS on surveying in the United States have been conducted. Leveson (2015) assumed 100% adoption of GPS in surveying and productivity gains of 45 to 55% and estimated that GPS provided benefits of between $9.8 and $13.4 billion in 2013 ($10.4 and $14.2 billion in 2017$). Similarly, Pham (2011) estimated the annual benefits of GPS to engineering construction (including heavy and civil and surveying and mapping) to be between $9.2 and $23 billion in 2007 ($10.7 and $26.8 billion in 2017$), based on an adoption rate of 40% and 100% respectively. These studies estimated economic benefits for only 1 year, assumed efficiency gains based on few sources, did not explicitly account for the costs of GPS-enabled surveying equipment, and did not differentiate between adoption rates or efficiency gains for different surveying applications.

Through expert interviews conducted by RTI, surveyors provided a detailed accounting of the timeline and key milestones in the adoption of GPS (see Figure 4). The first experimental phases of GPS receiver development occurred in the late 1970s and early 1980s, and surveyors in large firms and organizations like the National Geodetic Survey (NGS) were among some of the first adopters during this time. GPS provides greater returns on large surveying projects, and in its early days, only organizations undertaking large surveying projects found the high costs worthwhile.

Surveyors began widespread adoption in the 1990s as a result of technological development, in particular differential GPS, RTK networks, and NGS’s establishment of Continuously Operating Reference Systems (CORS) [24]. RTK technology, first introduced in 1992, allowed moment-by-moment GPS updates while in motion, increasing accuracy and speed of data acquisition. Before the full constellation of

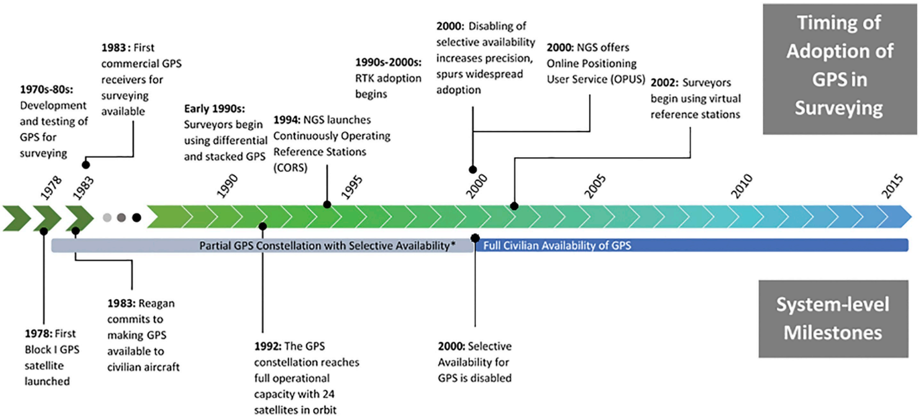

Figure 4. Timeline of relevant events in the history of GPS in surveying in the United States

satellites launched in 1995, a reliable GPS signal was not available 24 hours per day, and surveyors had to plan around its availability, leading to some impractical late-night availability and discontinuous periods. Benefits of adopting GPS also increased with general technological improvements that made equipment smaller and faster, lowered prices, and increased ease of use. These technologies allowed surveyors to obtain reliable and highly accurate measurements without needing a line of sight to the next survey point. However, GPS equipment was still prohibitively expensive for many surveyors.

Selective availability was turned off in 2000, further facilitating GPS's adoption. By the early 2000s, capital costs fell further, and virtual reference stations became widely available, a technology that allowed surveyors to quickly access a GPS signal from nearly any location. Other sectors that require highly accurate location information such as agriculture, and extractive industries also benefitted from these developments [25]. Through the further expansion of CORS and the incorporation of the GPS into the National Spatial Reference System (NSRS), surveyors could measure absolute locations rather than relative points, so locations from different geographies were on the same system and could be compared with each other. By 2010, surveyors had widely adopted GPS or GPS-assisted technology in their work; one expert remarked that by the late 2000s most surveyors could not afford to *not* use GPS.

The timeline, key trends, and milestones presented here are largely validated by the web-based survey that RTI conducted of National Society of Professional Surveyors (NSPS) membership.

4.10 Telematics

Telematics is a field of technology that uses in-vehicle equipment to remotely monitor vehicles for a variety of purposes. The high-precision capabilities of GPS are critical to unlocking most of the benefits of telematics. This case study focuses on the use of telematics devices in on-road commercial vehicles to increase operational efficiency, encourage driver behavior change to increase safety, optimize routing, and increase productivity.

The use of GPS in telematics has resulted in net benefits close to $330 billion between 2000 and 2017. In the event of a 30-day GPS outage, telematics users would experience, at a minimum, a loss of some labor and fuel savings benefits. In those industries in which telematics is tightly integrated into core business processes, users may experience a more serious business disruption. We conservatively estimate that the economic impact of a 30-day outage in the telematics sector could be between $3.2 and $6.3 billion. See Table 13.

Telematics devices gather data from multiple sources to gain insight into the position, direction, speed, and condition of the vehicle being monitored. The enabling data stream is the real-time location data provided by GPS. Other sensors include accelerometers and the internal vehicle computer, which monitors the condition of the vehicle and can also relay information about speed, intensity of acceleration, wheel angle, and whether a vehicle is in reverse. One expert commented that in the absence of GPS other data streams would be in effect “useless” in a matter of minutes.

The most common end users are in industries with large fleets of vehicles, including

- shipping and logistics;
- construction;
- field service sectors (e.g., home repair, plumbing, lawn service, on-demand roadside assistance for freight companies); and
- utilities (e.g., electricity, water, gas, and telecom providers).

Features of telematics services for which GPS generates significant benefits include real-time location awareness, navigation assistance, driver behavior monitoring, and vehicle condition monitoring. Table 13 describes these features and their benefits in detail.

The first version of a modern telematics device using real-time location data was the OmniTracs system by Qualcomm, which came on the market in 1988 and used a private satellite constellation to provide location data that were accurate to

Table 13. Features and benefits of telematics

Feature	Precision required	Description	Benefit
Driver behavior monitoring	5 m	GPS and other sensors collect data on speed, acceleration, harshness of braking, frequency of reversing, engine idling, and other behaviors that increase fuel consumption and the risk of accidents	• Reduced occurrence of accidents • Reduced fuel consumption and wear on the vehicle through more efficient driving behavior and idle reduction • Reduced insurance premiums
Real-time location awareness	50-100 m	GPS data can help dispatchers know in real time where all their vehicles are, aiding faster, more intelligent decisions about which vehicles to dispatch to which jobs based on their location and the work needs. Additionally, awareness that their location is being tracked can deter drivers from taking personal trips during the workday. Finally, location data can aid in the recovery of stolen vehicles	• Improved productivity • Reduced fuel consumption • Prevention of theft or reduced lost productivity from thefts
Navigation assistance	5 m	Turn-by-turn directions using GPS and digital map services can help drivers navigate to their next destination more efficiently	• Improved productivity • Reduced fuel consumption
Vehicle condition monitoring	5 m	Using GPS and data streams from the internal vehicle computer can help fleet managers anticipate mechanical problems and better manage preventive maintenance	• Reduced work disruptions due to unanticipated breakdowns • Lower maintenance expenses

approximately 1,000 feet [26]. The first telematics services to leverage GPS came on the market in the early to mid-1990s, which improved the accuracy of location data. Some of the first companies to offer GPS-based services were Rockwell and HighwayMaster, which used location data to provide automated mileage and route data collection systems (Satellite Today, 1996; TruckingInfo, 1996).

During the early stage of digital telematics adoption, hardware and service costs were high, making it cost prohibitive for smaller fleets to adopt. Additionally, wireless data transfer, if available, was expensive. Telematics users typically relied on downloading data at the end of a shift or trip, meaning that while drivers had real-time location awareness, dispatchers at fleet management offices did not have visibility of their drivers' real-time location. Turn-by-turn navigation, which helps optimize routing and reduce fuel consumption and vehicle miles traveled (VMT), was also not available.

In 2003, wireless telecom companies began to roll out the first wireless broadband networks, significantly expanding network coverage, reducing the cost of real-time data transfer, and causing an acceleration in telematics adoption. Telematics data are now used by many industries to optimize all aspects of fleet operations.

5. Summary of findings

The PNT signal provided by GPS enables many of the applications that companies rely on and that are integrated with modern American life. For the United States alone, we estimate that GPS has generated roughly $1.4 trillion in economic benefits (2017$) for the private sector in the years since it was made available for civilian use in the 1980s. Most of those benefits have accrued since 2010.

Our analysis combined insights from nearly 200 experts in the use of GPS for specific applications, surveys of professional surveyors and smartphone users, economic modeling tools, and national statistics. Because of the likelihood of measurement error, we recommended interpreting the point estimate of $1.4 trillion as a rough order of magnitude. The range of benefits to date is between $903 billion and $1.8 trillion. Benefits comprised productivity gains from new and existing products and services, improvements in quality, increases in personal enjoyment, and environmental and public health impacts.

5.1 Retrospective economic benefits

Table 14 summarizes the benefits we were able to quantify for each of the 10 sectors we analyzed. Benefits are largest for telecommunications, telematics (e.g., fleet management, logistics), and LBS (e.g., location features of smartphones and other personal devices). Relative to total industry size, GPS was particularly transformative for the professional surveying sector. Other industries, such as finance, leverage GPS because of its reliability and ubiquity, although the precision they are afforded is far

Table 14. Summary economic benefits of GPS for private-sector use, as of 2017

Sector	Specific analytical focus	Benefits ($Million)
Agriculture	Precision agriculture technologies and practices	$5,830
Electricity	Electrical system reliability and efficiency	$15,730
Finance	High-frequency trading	Negligible
Location-based services	Smartphone apps and consumer devices that use location services to deliver services and experiences	$215,702
Mining	Efficiency gains, cost reductions, and increased accuracy	$12,350
Maritime	Navigation, port operations, fishing, and recreational boating	Negligible
Oil and gas	Positioning for offshore drilling and exploration	$45,922
Surveying	Productivity gains, cost reductions, and increased accuracy in professional surveying	$48,124
Telecommunications	Improved reliability and bandwidth utilization for wireless networks	$685,990
Telematics	Efficiency gains, cost reductions, and environmental benefits through improved vehicle dispatch and navigation	$325,182
Total		$1,354,830

Note(s): Economic benefits were measured relative to a counterfactual that specified that preexisting sources of positioning, navigation, and timing information continued to be available in the absence of GPS. Thus, the relative benefit for some sectors is negligible but substantial for those with applications that have a requirement for GPS's accuracy and precision. We recommend interpreting the $1.4 trillion estimate as a rough order of magnitude. The range of benefits to date is estimated to be between $903 billion and $1.8 trillion

greater than what is required. Alternatives are or would have been readily available for them.

The magnitude of benefits for telecommunications, telematics, and LBS warrants additional explanation. Precision timing has a critical role in synchronization of telecommunications networks, enabling service providers to more efficiently use available spectrums and deliver high-speed wireless services. Given American society's intensive use of wireless technologies, it is perhaps not surprising that benefits related to telecommunications are substantial. Benefits relating to telematics and LBS have significant positive externalities beyond productivity impacts: improved navigation and fleet management reduces miles driven, generating environmental and public health benefits through reduced fuel combustion. And, of course, Americans enjoy all the location and navigation features of their personal devices.

In looking across the many sectors and applications that require GPS's accuracy and precision, it becomes clear that GPS has some attributes of a utility. The signal is a public good and service provided by the U.S. government that enables productivity, quality, and efficiency benefits that would not otherwise be possible. For many years, it was the only comprehensive PNT signal available. Signals are now available from GLONASS (Russia), Galileo (Europe), and BeiDou (China). The global marketplace means that many devices are increasingly capable of receiving signals from multiple constellations. In the United States, however, critical infrastructure, industries, and applications leverage the GPS signal.

The economic significance of GPS is growing. About 90% of GPS's benefits have accrued since 2010 (Figure 5). Long technology life cycles in some sectors, such as electric utilities, mean that although GPS-enabled equipment has been installed, legacy equipment is still in place. This means that the full potential of GPS functionality has yet to be realized.

5.2 *Potential impacts of a 30-day GPS outage*

The question of the potential impact of a 30-day outage was added to our scope during our analysis. The duration was specified by the Department of Commerce, and it is not

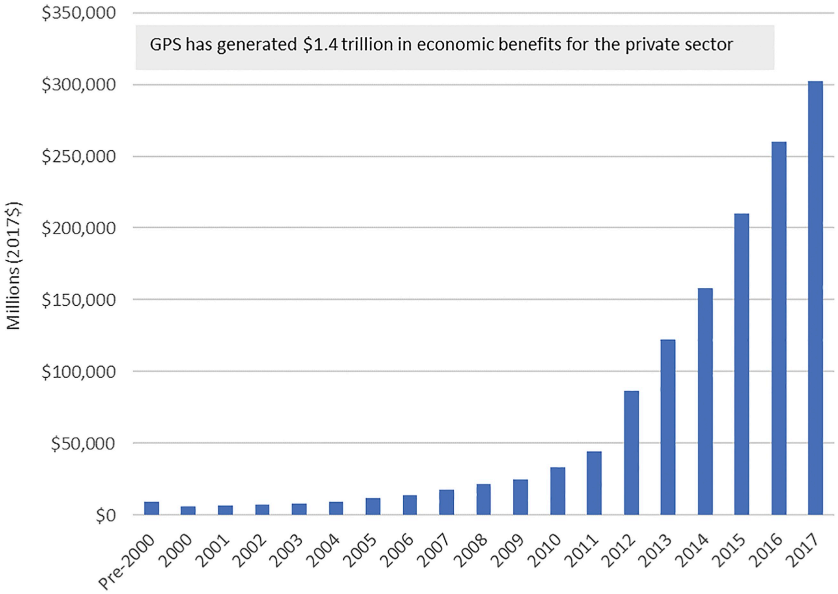

Figure 5. Time series of GPS's economic benefits for the private sector

known whether a severe space weather event or nefarious activity by a bad actor would or could cause such a long disruption.

Many technologies can “hold over” timing information or rely on technology alternatives, but a full 30-day outage could potentially have a $30 billion impact (range: $16 billion to $35 billion). If the outage were to occur during critical planting seasons for farmers, the impact could be as high as $45 billion. See Table 15.

The impact on Day 1 of an outage would differ from the impact on Day 10 or Day 30. That averages out to about $1 billion in daily loss of use (before accounting for agriculture). As with our retrospective benefits results, this estimate should be interpreted as a rough order of magnitude. If the outage were to occur during April or May, the impact on farmers would be significant, and the impact could be more than $1 billion per day.

Table 15. Potential impact of a 30-day GPS outage

Sector	Specific analytical focus	Benefits ($Million)
Electricity	Electrical system reliability and efficiency	$275
Finance	High-frequency trading	Negligible
Location-based services	Smartphone apps and consumer devices that use location services to deliver services and experiences	$2,859
Mining	Efficiency gains, cost reductions, and increased accuracy	$949
Maritime	Navigation, port operations, fishing, and recreational boating	$10,411
Oil and gas	Positioning for offshore drilling and exploration	$1,520
Surveying	Productivity gains, cost reductions, and increased accuracy in professional surveying	$331
Telecommunications	Improved reliability and bandwidth utilization for wireless networks	$9,816
Telematics	Efficiency gains, cost reductions, and environmental benefits through improved vehicle dispatch and navigation	$4,137
Total, Excluding Ag.	If the outage were not to occur during critical planting seasons	$30,298
Agriculture	Precision agriculture technologies and practices	$15,122
Total, Including Ag	If the outage were to occur during critical planting seasons	$45,420

Note(s): Range of potential losses is $16 to $35 billion, before accounting for losses of about $15 billion if a 30-day outage were to occur during critical planting seasons for U.S. farmers

The maritime sector had technologies and systems available that complemented mariners' skills. GPS's availability meant that the Loran system was no longer necessary, and the signal was turned off. This means that although the historical benefits relative to technology alternatives are negligible, if GPS were lost, there could be more than $10 billion in losses over 30 days. This loss estimate underscores the critical role GPS has come to play in economic activity.

5.3 Concluding observations

The comprehensive costs of GPS are difficult to characterize because of the system's emergence from multiple R&D programs over seven decades. Since 2010, expenditures have averaged roughly $1.3 billion per year (2017$) [27]. This estimate includes both defense and civilian development, procurement, and operations. A long history of investments, comingling of defense and nondefense funding to sustain and operate the system, and the large number of laboratories and agencies involved make estimation of a benefit-to-cost ratio (or another form of return-on-investment measure) difficult. The Department of Transportation receives appropriations for GPS's civilian use case, but most funding for GPS is provided by Congress to the Air Force.

One could compare GPS's comprehensive costs to only its private-sector benefits for 2010 through 2017. This produces a benefit-to-cost ratio of about 100 to 1 [28]. The civilian use portion is a fraction of total expenditure, so the ratio is likely an underestimate. If one assumes that 25% of GPS expenditures were related to civilian use cases, the ratio is about 400 to 1. If one assumes 40%, the ratio is 250 to 1. If one were to guess that the spend on GPS has been more or less constant since President Reagan first permitted civilian use, the ratio is closer to 10 to 1. This does not mean that other investments or programs will have such a high impact; this is simply what we observe within an 8-year window in the 2010s from a program launched in 1973 that itself has roots in programs from the 1960s. It would be a mistake to assume that a comparable investment would achieve these results. The math is less important than the outcome: making GPS available for private-sector use was a good idea.

An important observation from trying to tease out some sense of the return on investment is the relationships between science investments, private-sector innovation, and time. GPS was fully operationally in 1995. It was used by several industries for positioning in the 1980s and 1990s, but the majority of benefits began to accrue during the technology boom starting in the late 1990s. The availability of a reliable, accurate, and extremely precise timing signal meant that innovators had one less barrier to their development of the technologies and applications that are pervasive today and that generate the lion's share of GPS's economic benefits. GPS was a resource whose quality was known, and it took time for innovators to leverage the service. The combination of rapid advances in information technology and GPS was clearly transformative. Excellent examples are telematics and LBS.

GPS is not just a service; it is also a platform for innovation. With the support of federal agencies, private enterprise has leveraged GPS to deliver value through precision agriculture, advanced logistics and route optimization, high-speed wireless services, and a host of other applications.

For most Americans, the impact of GPS is as near as their smartphone. Maps and navigation tools, social networking, shopping, dating, and relationships are all supported by their phones' location services. GPS is a link between innovation within the national lab system, technology transfer to the private sector, and the tools of their everyday lives.

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Notes

[1.] This monograph draws on earlier work on GPS (O'Connor *et al.*, 2019).

[2.] UTC is the international time standard that is maintained by the Bureau International des Poids et Mesures. UTC is based on International Atomic Time, which is an average of over 300 atomic clocks at 60 timing laboratories where the clocks are weighted based on stability. GPS's primary signal distributes UTC, which enables networks to stay in sync across wide geographic areas (NRC, 2016).

[3.] Directed by DoD, the U.S. Naval Observatory is tasked with maintaining the time and frequency standard for all DoD activities. The primary "master clock," which provides the time standard for GPS and all other DoD timing needs, is managed by the U.S. Naval Observatory in Washington, DC. A secondary master clock is located at Shriever Air Force Base. The master clocks incorporate multiple cesium atomic clocks and hydrogen masers. GPS time differs slightly from UTC in that it is not corrected to match the rotation of the Earth. UTC does this by periodically adding leap seconds and making other corrections. In addition to GPS time, the GPS signal distributes the correction between GPS time and UTC (NIST, 2016).

[4.] One can think of the four satellites as providing the information to solve for four unknowns: longitude, latitude, altitude, and the timing error of the receiving source.

[5.] This summary describes the state of GPS technology development as of 2019. GPS technology advances slowly. Perhaps the topics in this monography might be revisited in the next decade.

[6.] This is an abbreviated version of a table in ATIS (2017), a report that details the timing requirements of the telecom sector and examines the vulnerabilities posed by reliance GPS without a backup system.

[7.] One way to assist users with identifying their starting place in such apps would be to use cell towers for positioning. This was an approach used in a beta version of Google Maps with My Location, which was temporarily available for smartphones that did not have GPS capabilities (Gohring, 2007).

[8.] The Mazda Eunos Cosmo was the first production car with a built-in GPS navigation system. It was produced for the Japanese market (Leite, 2018).

[9.] Funding for assessing the benefits of GPS for maritime industries was provided by the Department of Homeland Security's Cybersecurity and Infrastructure Security Agency.

[10.] For additional detail, see gyrocompass www.marineinsight.com/marine-navigation/gyro-compass-on-ships-construction-working-and-usage/

[11.] For more information, visit https://nauticalcharts.noaa.gov/charts/noaa-enc.html

[12.] For more information, visit www.nga.mil/ProductsServices/NauticalHy-drographicBathymetricProduct/Pages/DigitalNauticalChart.aspx

[13.] Some surveying activities could be delayed.

[14.] Underground mines rely on other positioning technologies such as RFID and Wi-Fi trilateration (Li *et al.*, 2015) and SLAM.

[15.] Active mines are those that report operator employment during the year. Mines at which only contractors were working did not show any employment and are not displayed.

[16.] www.austmine.com.au/News/rio-tinto39s-kennecott-mine-a-hub-for-innovation-1

[17.] This is defined as the productivity gains made possible by GPS minus the productivity gains that would have been possible with alternative technologies had GPS not been made available for civilian use. As in the other cases, we refer to this alternative scenario as the "counterfactual."

[18.] Benefits of GPS for midstream and downstream operations are captured by other case studies, such as maritime navigation and telematics, and are excluded from this section. Use of GPS for onshore operations is captured in the surveying analysis.

[19.] Approximate position accuracy is 8-20 m (26.2-65.6 ft) from the GPS Wide Area Augmentation Systems (WAAS) 2008 Performance Standard.

[20.] www.bls.gov/oes/2017/may/oes171022.htm

[21.] Extrapolated from historical revenue – see Table X-2.

[22.] A geodetic network or geodetic control network is a system of points represented by physical monuments that are precisely marked and documented. The National Spatial Reference System is an example of geodetic control network across the United States.

[23.] RTK is a technique that uses carrier-based ranging to provide positioning information that is much more precise than code-based positioning techniques.

[24.] The Continuously Operating Reference Stations (CORS) is a network of independently owned and operated sites that provide three dimensional positioning for the United States and its territories. NGS oversees the network, which provides highly accurate GPS positioning data relative to the National Spatial Reference System. The Online Positioning User Service (OPUS) relies on CORS to provide any survey grade GPS user with data to link their GPS position with to the NSRS. For more info on CORS and OPUS, visit: www.ngs.noaa.gov/CORS/ and www.ngs.noaa.gov/OPUS/about.jsp

[25.] To avoid double counting, these benefits are not included in the surveying sector analysis of this study but are captured in the related agriculture and mining sections of this report.

[26.] Prior to digital telematics, the earliest version of an analog telematics device is the analog tachograph, which used a wax-coated paper disc to record data on the speed, distance, and activity mode of the driver. Typically, a single disc stored 24 hours of data, which could be analyzed after the fact to monitor how many hours a driver worked and provide basic insights into driving behavior.

[27.] See www.gps.gov/policy/funding/

[28.] Benefits (2017$) for 2010 through 2017 were discounted using a 7% social discount rate, per OMB Circular A-94. Costs for FY2010 through 2017 were adjusted to 2017$ using the real GDP index and discounted. Costs were assumed to be incurred at the beginning of a period and benefits at the end of a period. The benefit-cost ratio is the ratio of the present value of benefits (numerator) to the present value of costs (denominator).

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About the author

Alan C. O'Connor is a Senior Economist and Vice President for Strategic Consulting at RTI International, an independent research institute. He received the B.A. degree in economics and political science from the University of North Carolina at Chapel Hill, and the MBA degree from the Middlebury Institute of International Studies at Monterey.

Mr. O'Connor has 25 years of experience in R&D policy and programs, academic entrepreneurship, economic development, and research impact assessment. His core practice consists of program evaluations, benefit-cost analyses, retrospective and prospective social return on investment studies, and program strategy and learning. He has significant experience with R&D program evaluation, academic entrepreneurship, and applied economics. He has evaluated the impact of research infrastructure, entrepreneurship programs, and major advances in technology. He also has provided strategy and evaluation support for several SBIR/STTR portfolios as well as proof-of-concept programs, such as the NIH Centers for Accelerated Innovation and the Research Evaluation and Commercialization Hubs programs.

Mr. O'Connor is co-author of *Battery Technology for Electric Vehicles: Public Science and Private Innovation* (Routledge, 2015), co-editor of *Public Investments in Energy Technology* (Edward Elgar, 2012), and co-author of numerous domestic and international government reports.

His scholarship has also appeared in such journals as *Science and Public Policy, Small Business Economics*, *The Journal of Technology Transfer*, *Annals of Science and Technology Policy*, *Annals of the New York Academy of Sciences*, *Vaccine*, *The American Journal of Managed Care*, and *Economics of Innovation and New Technology.*

Mr. O'Connor is globally regarded as an expert on program evaluation methodology and methods; he consults internationally through RTI International. Alan C. O'Connor can be contacted at: oconnor@rti.org