GPS Dependencies in the Transportation Sector

An Inventory of Global Positioning System Dependencies in the Transportation Sector, Best Practices for Improved Robustness of GPS Devices, and Potential Alternative Solutions for Positioning, Navigation and Timing

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The John A. Volpe National Transportation Systems Center (Volpe Center) was asked by the NOAA Office of Space Commercialization to analyze dependencies on Global Positioning System (GPS) positioning, navigation, and timing (PNT) services within the U.S. National Transportation System (NTS). The Volpe Center identified over 50 different systems and applications (including general groupings of systems or applications) that depend upon accurate, reliable and continuous availability of GPS PNT signals. In addition, the Volpe Center identified a number of best practices that can be utilized by government and civil users of GPS receivers, to improve the robustness and resilience of those devices. Finally, the Volpe Center mapped existing and emerging technologies that can be used as alternative sources of positioning, navigation and/or timing signals, in the event the GPS service is lost or degraded.

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List of Abbreviations and Terms

Abbreviation or Term	Description
2D	Two-dimensional (e.g., latitude and longitude)
3D	Three-dimensional (e.g., latitude, longitude and altitude above a defined geographic or marine baseline surface)
ADS-B	Automatic Dependent Surveillance – Broadcast
AFS	Atomic Frequency Standard
AIS	Automatic Identification System
APNT	Alternative Positioning, Navigation, and Timing
ARPA	Automatic Radar Plotting Aid
ATON	Aid-to-Navigation
Beidou	A global navigation satellite system developed and deployed by the People's Republic of China
BVLOS	Beyond visual line-of-sight
BRT	Bus Rapid Transit
CORS	Continuously Operating Reference Stations, a ground-based GPS augmentation service delivered by the National Oceanic and Atmospheric Administration
COTS	Commercial off-the-shelf
dBm	Decibel-milliwatts (measured power ratio of a radio signal, referenced to one milliwatt)
DFDR	Digital Flight Data Recorder
DGPS	Differential Global Positioning System
DHS	Department of Homeland Security
DIS	Draft Information System
DSRC	Dedicated Short-Range Communication
ECDIS	Electronic Chart Display and Information System
EGNOS	European Geostationary Navigation Overlay Service
ELD	Electronic Logging Device
ELT	Emergency Locator Transmitter
EPIRB	Emergency Position Indicating Radio Beacon
EU	European Union
FAA	Federal Aviation Administration (a modal agency of U.S. DOT)
FDM	Flight Data Monitoring Systems
FHWA	Federal Highway Administration (a modal agency of U.S. DOT)
FMCSA	Federal Motor Carriers Safety Administration (a modal agency of U.S. DOT)
FRA	Federal Railroad Administration (a modal agency of U.S. DOT)
FTA	Federal Transit Administration (a modal agency of U.S. DOT)
GAGAN	GPS Aided Geo Augmented Navigation [system]
Galileo	A global navigation satellite system developed and deployed by the European Union
GBAS	Ground-Based Augmentation System
GIS	Geographic Information System
GLONASS	A global navigation satellite system developed and deployed by the Russian Federal Space Agency

Abbreviation or Term	Description
GMDSS	Global Maritime Distress and Safety System
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPRS	General Packet Radio Service
GPS	Global Positioning System
ICS	Industrial Control Systems
IMO	International Maritime Organization
IRNSS	Indian Regional Navigation Satellite System, a global navigation satellite system developed and deployed by the Republic of India
ITS	Intelligent Transportation Systems
ITS	Intelligent Transportation Systems
MARAD	Maritime Administration (a modal agency of U.S. DOT)
MSAS	Multi-functional Satellite Augmentation System
NASA	National Aeronautics and Space Administration
NAVSTAR	A global navigation satellite system developed and deployed by the United States (more commonly referred to as the U.S. GPS system)
NEXRAD	Next-Generation Radar (WSR-88D)
NEXTGEN	Next Generation Air Transport System
NDGPS	Nationwide Differential GPS [service]
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSRS	National Spatial Reference System
NWS	National Weather Service
OEM	Original equipment manufacturer
PBN	Performance-based navigation
PHMSA	Pipeline and Hazardous Material Safety Administration (a modal agency of U.S. DOT)
PNT	Positioning, Navigation, and Timing
PTC	Positive Train Control
QZSS	The Quasi-Zenith Satellite System, a proposed three-satellite regional time transfer system and satellite-based GPS augmentation system under development by Japan, which would be available in the greater Japan region.
RF	Radio frequency
RIS	River Information System
RNAV	Area navigation
RNP	Required Navigation Performance
RNSS	Radio Navigation Satellite Service
RODS	Record of Duty Status
SDCM	System for Differential Corrections and Monitoring
SLSDC	Saint Lawrence Seaway Development Corporation (U.S.)
SLSMC	St. Lawrence Seaway Management Corporation (Canada)
SPS	Standard Positioning Service of the U.S. GPS system
SUE	Subsurface Utility Engineering
TAWS	Terrain Awareness and Warning System
TBO	Trajectory-based operations

Abbreviation or Term	Description
TFDU	Time and Frequency Distribution Unit
TFS	Timing and Frequency System
TDWR	Terminal Doppler Weather Radar
TNC	Transportation Network Companies
UAS	Unmanned Aircraft System
UAT	Universal Access Transmitter
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
USDOT	U.S. Department of Transportation
USNO	U.S. Naval Observatory
V2X	General term that includes Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), or Vehicle-to-Pedestrian (V2P) applications of DSRC
VDR	Voyage Data Recorder
VHF	Very High Frequency (a radio frequency band from 30 MHz to 300 MHz)
VLOS	Visual line-of-sight
VMS	Vessel Monitoring System
VTS	Vessel Traffic Services
WAAS	Wide-Area Augmentation System
WWVB	A time signal radio station located near Fort Collins, Colorado operated by the National Institute of Standards and Technology

1. Introduction

1.1. Overview of the U.S. Global Positioning System

The U.S. Global Positioning System (GPS) was originally developed by the U.S. Department of Defense to improve en route navigation and positioning for military purposes.[1] The first GPS satellites were launched in 1978, with the full 24-satellite constellation declared operational in July 1995.[2] The GPS network of satellites and ground facilities is operated by the U.S. Air Force 50th Space Wing, located Schriever Air Force Base, Colorado Springs, Colorado.[3] The system consists of three segments:

- The space segment, consisting of a constellation of satellites that transmit signals to users (see figure 1-1). The key component of each satellite is an accurate clock, comprised of an atomic oscillator with a rubidium cell and cesium beam, with an accuracy of one second in 300,000 years.[4] Satellites have a design life from 7 to 12 years and transmit in Radio Navigation Satellite Service (RNSS) frequencies bands (1164-1215 MHz & 1559-1610 MHz).

Figure 1-1: Block IIR(M) GPS Satellite

Source: GPS.GOV

[1] The U.S. Global Navigation Satellite System is officially known as the NAVSTAR (NAVigation Satellite Timing And Ranging) System; however, this report will refer to it the U.S. Global Positioning System or GPS.

[2] "GPS: A generation of service to the world," U.S. Air Force press release, June 25, 2015, available at www.af.mil/News/ArticleDisplay/tabid/223/Article/601748/gps-a-generation-of-service-to-the-world.aspx, accessed August 22, 2016.

[3] 50th Space Wing website, available at www.schriever.af.mil/About-Us/Fact-Sheets/Display/Article/275809/50th-space-wing, accessed August 22, 2016.

[4] "U.S. global positioning satellites: NAVSTAR GPS," spacetoday.org website, available at www.spacetoday.org/Satellites/GPS.html, accessed July 29, 2016.

- The control segment, consisting of a global network of ground facilities that track the GPS satellites, monitor transmissions, perform analyses, and send commands and data to the constellation (see figure 1-2).[5]

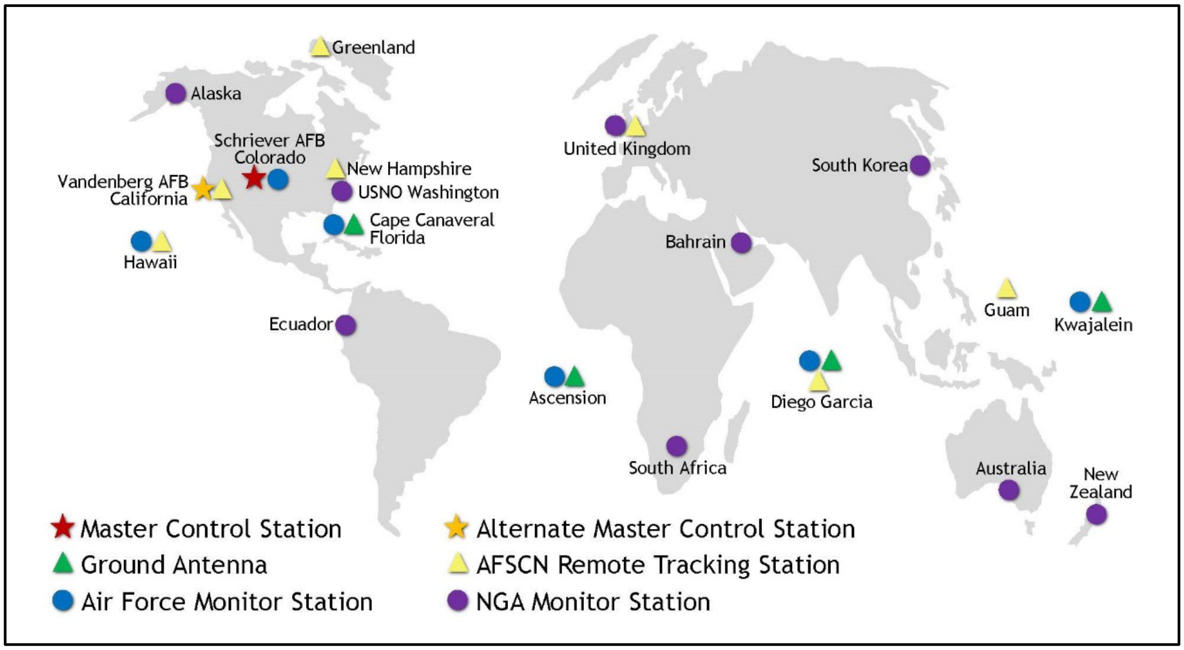

Figure 1-2: GPS Control Segment (April 2016)

Source: GPS.GOV

- The user segment, consisting of GPS antennas and receivers operating in space, in the air, on the seas, or on land.

Although GPS was conceived as a military positioning, navigation and timing (PNT) system, its potential as civilian PNT system was apparent form the start. The first commercially-available GPS receiver, the Texas Instruments TI 4100 NAVSTAR Navigator, was introduced in 1981, as the result of a multi-agency contract administered by Applied Research Laboratory of the University of Texas and funded by the Defense Mapping Agency, National Geodetic Survey, and the U.S. Geological Survey. At nearly 59 pounds, it was hardly considered "portable" and took nearly 20 minutes to initially acquire a position.[6] More significant, it cost over $119,000, putting it out of reach of most users.[7]

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[5] "Control Segment," GPS.GOV website, available at www.gps.gov/systems/gps/control/, accessed August 20, 2016.
[6] "Texas Instruments TI 4100 NAVSTAR Navigator," Institute of Navigation, Navigation Museum website, available at www.ion.org/museum/item_view.cfm?cid=7&scid=9&iid=22, accessed August 16, 2016.
[7] "Texas Instruments GPS Receiver," Smithsonian Institution website, available at http://americanhistory.si.edu/collections/search/object/nmah_998407, accessed August 16, 2016.

Commercial manufacturers and potential users began to recognize the system's potential, particularly as additional satellites were launched to increase global coverage and signal availability. In 1988, Magellan Navigation Systems introduced the NAV 1000, the first handheld GPS unit. Weighing just 1.5 pounds and with a price-tag of only $3,000, the NAV 100 marked a new era in GPS civilian and commercial use.[8] Today, the smallest GPS receivers – some just 4.1 millimeters (0.16 inches) square (see figure 1-3) – cost less than $100, and are found in cars, planes, ships, wristwatches, and smartphones, with over four billion GPS-enabled devices estimated in service worldwide.[9]

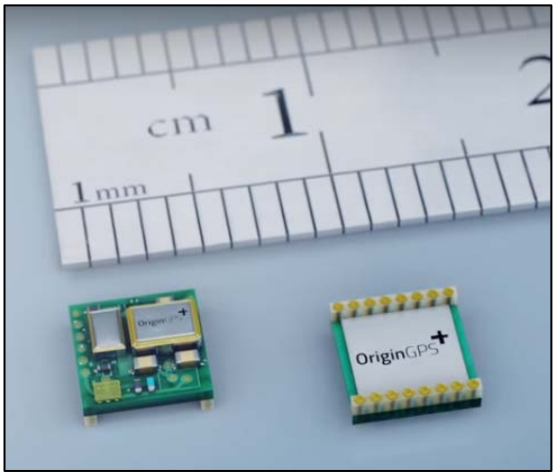

Figure 1-3: Highly Miniaturized GPS Receiver

Source: OriginGPS

In 1996, GPS was formally declared a military-civilian, dual-use system.[10] Four years later, the "selective availability" feature, which intentionally degraded the quality of the GPS signal available to civilian users by introducing errors of 50-100 meters, was turned off, increasing the precision of GPS position and opening the door to its widespread adoption for civilian PNT applications.[11] Advances in miniaturization of GPS receiver technology, along with a revolution in the development of computer-based geographic information system (GIS) applications – whether mapping, surveying, routing, fleet management, asset recovery, or package tracking – encouraged innovation, spurred growth, and opened new markets beyond basic point-to-point

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[8] "Magellan NAV 1000 GPS Receiver, 1988," Smithsonian Institution website, https://timeandnavigation.si.edu/multimedia-asset/magellan-nav-1000-gps-receiver-1988, accessed August 16, 2016.
[9] "GPS: A generation of service to the world," op cit.
[10] "Presidential Decision Directive/National Science and Technology Council-6, U.S. Global Positioning System Policy," The White House, March 28, 1996, available at http://clinton3.nara.gov/wh/eop/ostp/nstc/html/pdd6.html, accessed August 16, 2016.
[11] "Selective Availability," GPS.GOV website, available at www.gps.gov/systems/gps/modernization/sa/, accessed August 16, 2016.

navigation. Today, GPS has become the ubiquitous GNSS, and a gold-standard for PNT services in the U.S. and around the globe. With an ever-increasing dependence upon GPS for more and more PNT applications, the safety and efficiency of the U.S. National Transportation System (NTS) relies upon GPS around the clock.

The U.S. GPS program receives national-level attention and guidance from a joint civil/military body called the National Executive Committee for Space-Based Positioning, Navigation, and Timing, co-chaired by the Chief Information Officer of the Department of Defense (DOD) and the Assistant Secretary of Transportation for Research and Technology.[12] The U.S. Department of Transportation (USDOT) is the lead Federal agency on GPS-related issues and has lead responsibility for developing requirements for civilian applications.[13] The Department of Homeland Security (DHS), through the U.S. Coast Guard (USCG) Navigation Center, provides user support to the civilian, non-aviation GPS community, while the Federal Aviation Administration supports the civilian aviation GPS community.

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[12] "Governance," GPS.GOV website, available at www.gps.gov/governance/excom/groups/#esg, accessed August 16, 2016.

[13] "U.S. Space-Based Positioning, Navigation and Timing Policy Fact Sheet," December 2004, available at www.whitehouse.gov/files/documents/ostp/Issues/factsheetspace-basedpositioningnavigationtiming.pdf, accessed August 22, 2016.

1.2. Disruptions in GPS Service

For this report, we explored five broad categories of GPS disruption, which are described below. We did not consider the specific sources of any disruption, nor the potential threat or risks associated with each category, since it was beyond the scope of this project.[14]

Spectrum encroachment from radio emissions in nearby radiofrequency bands can cause interference to the GPS signal when the stronger radio signals overpower the relatively weak GPS signals from space. Additionally, according to the FCC, the sensitivity of some GPS receivers allows them to process the weak signals received from GPS satellites, but which makes them vulnerable to interference from RF emissions from nearby bands. With this type of interference, GPS devices pick up the stronger radio signals and become ineffective.

Space weather can also cause interference to GPS signals. For example, during solar flare eruptions, the sun produces radio waves that can interfere with a broad range of frequencies, including those frequencies used by GPS.[15] Some space weather phenomena occur in predictable cycles, which allows GPS system operators to alert users to potential degradations in service. Space weather is tracked by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center.[16]

GPS infrastructure disruptions can include unscheduled system maintenance, intentional tampering with, or destruction of GPS operating systems or infrastructure (satellites, ground stations, etc.). The U.S. Federal Government maintains a public website that includes information on current and scheduled service outages, which also includes a portal to report any suspected outages.[17]

Jamming involves the use of radio frequency transmitters broadcasting a signal across one or more GPS/GNSS frequency to raise the noise level or overload the receiver circuitry and cause a loss of signal lock. Although they can be easily purchased online, it is illegal to sell, buy or use any type of GPS jamming device in the U.S. and in many other countries.[18]

Spoofing involves the replacement of a true satellite signal with a manipulated signal, whereby the user may not realize they are using an incorrect GPS signal and may continue to rely on it.

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[14] For a detailed discussion on the vulnerabilities, risks, and threats to GPS, see, "National Risk Estimate: Risks to U.S. Critical Infrastructure from Global Positioning System Disruptions," Homeland Infrastructure Threat and Risk Analysis Center, U.S. Department of Homeland Security, Washington, 2012, available at www.rntfnd.org/wp-content/uploads/DHS-National-Risk-Estimate-GPS-Disruptions.pdf, accessed August 19, 2016.

[15] "Space Weather," READY.GOV website, available at www.ready.gov/space-weather, accessed August 19, 2016.

[16] NOAA Space Weather Prediction Center website, available at www.swpc.noaa.gov/, accessed August 19, 2016.

[17] See GPS.GOV website at www.gps.gov/support/user/, accessed August 19, 2016.

[18] "Jammer Enforcement," Federal Communications Commission website, available at www.fcc.gov/general/jammer-enforcement, accessed August 22, 2016.

A spoofed GPS signal can cause a GPS receiver to estimate a false position, a false time, or both. Articles and lab experiments have illustrated potential for harm from spoofing attacks in the electrical power grid system, maritime navigation, financial markets, and mobile communications, among other critical infrastructure sectors.

GPS disruptions can be described by a number of bivariate characteristics, which are described in Table 1-2:

Table 1-1: Characteristics of GPS Disruptions

Characteristic	Example
Unintentional vs. Intentional	Is the disruption caused by a piece of space debris that disabled a GPS satellite or is it due to an intentional act by a disgruntled employee or terrorist?
Predictable vs. Unpredictable	Was the disruption due to an anticipated increase in solar flare activity or the sudden activation of a jamming device?
Environmental vs. Manmade	Is the disruption due to increased solar weather activity or due to an improperly configured radio transmitter operating in an adjacent frequency band?
Crude vs. Sophisticated	Is the disruption caused by a $50 GPS jammer purchased on-line, or by a hacker precisely manipulating a GPS signal to deceive shipping or highway traffic?
Local vs. Widespread	Is the disruption a targeted spoofing attack against a single cargo terminal, or does it cover a large geographic area (e.g., due to a significant solar weather phenomenon)?

Source: Volpe Center

Table 1-2 maps the five general categories of GPS disruptions against the characteristics described above.

Table 1-2: GPS Disruptions vs. Characteristics

<table>
<tr><th></th><th>Spectrum Encroachment</th><th>Solar Weather</th><th>GPS Infrastructure</th><th>Jamming</th><th>Spoofing</th></tr>
<tr><td rowspan="2">Unintentional or Intentional</td><td colspan="3">UNINTENTIONAL</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">INTENTIONAL</td></tr>
<tr><td rowspan="2">Predictable or Unpredictable</td><td colspan="3">PREDICTABLE</td><td></td><td></td></tr>
<tr><td colspan="5">UNPREDICTABLE</td></tr>
<tr><td rowspan="2">Environmental or Manmade</td><td></td><td colspan="2">ENVIRONMENTAL</td><td></td><td></td></tr>
<tr><td>MANMADE</td><td></td><td colspan="3">MANMADE</td></tr>
<tr><td rowspan="2">Crude or Sophisticated</td><td colspan="4">CRUDE</td><td></td></tr>
<tr><td></td><td></td><td colspan="3">SOPHISTICATED</td></tr>
<tr><td rowspan="2">Local or Widespread</td><td>LOCAL</td><td></td><td colspan="3">LOCAL</td></tr>
<tr><td colspan="4">WIDESPREAD</td><td></td></tr>
</table>

Source: Volpe Center

2. Identification of GPS Dependencies in the Transportation Sector

2.1. Methodology

This report does not attempt to identify all specific systems, applications, or devices that rely upon GPS signals for positioning, navigation or timing. Such an inventory would be hundreds of pages long and immediately out of date. Rather, we attempt to identify broad groups of systems and applications across transportation modes that rely upon GPS signals to support the safe and efficient operation of the NTS. Identical or similar systems can be found across multiple modes, while some applications are unique or predominant in specific modes.

In order to compare dependencies across different modes, each system or application will be explored using four common parameters:

1. **Functional Purpose**

Position The system determines a precise physical position in two or three dimensions.

Navigation The system facilitates safe and efficient travel between two or more known physical positions.

Timing The system provides a precise timestamp for use by an individual device, which is accurate across multiple devices and/or multiple systems.

2. **User Community**

Federal Federal agencies (e.g., USDOT, FEMA, SLSDC, Amtrak, etc.)

State State and regional agencies (e.g., state departments of transportation, emergency management, environmental conservation)

Local Cities and towns, and their municipal agencies (e.g., law enforcement, emergency responders, transit agencies)

Private Private transportation users (e.g., individual vehicle operators, passengers, transit riders or system users)

Commercial Commercial users, such as shippers, carriers, fleet operators, or transit system operators, as well as third-party entities that support the NTS (e.g., highway survey and construction firms)

3. **Principal Operating Environment**

Space Signals are used for three-dimensional PNT purposes in space (i.e., at altitudes of 100 km or higher)

Air Civil aviation, including unmanned aircraft systems (from the airport surface, up to altitudes of 100 km)

Surface Any vehicles operating on a roadway, railway, transit line, or waterway

Subsurface Energy and hazardous materials pipelines beneath the earth's surface[19] [20]

4. **Principal Operating Platform**

Vehicle The GPS-based system or application is primarily vehicle-based, whether in an aircraft, automobile, train, truck, transit vehicle, boat or ship.

Infrastructure The GPS-based system or application is primarily used to construct, maintain, repair, or operate transportation system infrastructure.

System The GPS-based system or application is used to support the safe operation of an entire transportation system or portion thereof, using PNT data from both vehicle- and infrastructure-based devices.

In conducting this inventory, this section will first identify dependencies shared across multiple transportation modes. For example, the most basic functions of a GPS receiver are to determine a precise geographic location (positioning) and a precise time (timing) that is accurate across multiple devices and systems. These functions can be found in the GPS devices fitted in planes, trains, and automobiles, as well as in cell phones and portable devices carried by vehicle operators, pilots, or passengers. There are also GPS-dependent systems such as weather satellites that transportation systems and travelers rely upon for safe and efficient operation.

Second, this section lists GPS dependencies that are primarily found, or unique to, individual transportation modes. Examples include the Wide-Area Augmentation System (WAAS) developed to improve aircraft navigation, the Automatic Identification System (AIS) used aboard ships to improve maritime security, or automobile remote crash detection systems such as OnStar® that improve emergency response by providing precise locations of accidents or

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[19] While GPS and most other radionavigation signals do not penetrate below ground level, the signals may be received and/or used by surface-based systems to support the operations of subsurface systems.
[20] This report only covers GPS dependencies of pipelines regulated by the Pipeline and Hazardous Materials Safety Administration (i.e., those pipelines used to transport energy and hazardous materials). However, some of the same GPS dependencies identified herein also apply to non-hazardous pipelines (e.g., water, sewage, etc.).

medical emergencies. These mode-specific GPS dependencies are examined in four broad groups: aviation, surface-maritime transportation, surface-ground transportation (including highways, rail and transit), and sub-surface (pipelines). The modal grouping, including the responsible USDOT agencies, is shown in table 2-1.

Table 2-1: Modal Groupings

Aviation	<u>DOT Modal agencies</u>: Federal Aviation Administration (aircraft) <u>Coverage</u>: All domestic airspace, as well as global airspace traversed by U.S. registered aircraft. <u>Application</u>: All U.S. civil aircraft (commercial and recreational), whether publically- or privately-owned; airport infrastructure.
Surface: Maritime Transportation	<u>DOT Modal agencies</u>: U.S. Coast Guard (ships and private vessels), U.S. Maritime Administration (ships), St. Lawrence Seaway Development Corporation (ships operating on the St. Lawrence Seaway) (see note). <u>Coverage</u>: All oceans, U.S. coastal waters, inland lakes, rivers and waterways. <u>Application</u>: Operators of commercial vessels (e.g., cargo, fishing, passenger, tugboats, dredges), publicly-owned vessels (e.g., ferries, law enforcement, fireboats), and privately-owned pleasure craft; port and waterway infrastructure.
Surface: Ground Transportation	<u>USDOT Modal agencies</u>: Federal Highway Administration (highways), National Highway Traffic Safety Administration (automobiles), Federal Motor Carriers Safety Administration (trucks and motorcoaches), Federal Railroad Administration (freight and passenger rail), Federal Transit Administration (public transit). <u>Coverage</u>: All highway and roadway infrastructure (arterial, collector, feeder), including urban, rural, paved and unpaved roadways; all freight and passenger railways; all rail or roadway transit rights of way. <u>Application</u>: Publically- or privately-owned passenger vehicles, light trucks, commercial motor vehicles, freight rail, passenger rail, and transit vehicles (light rail, heavy rail, bus, trolley, bus rapid transit).
Subsurface	<u>USDOT Modal agency</u>: Pipeline and Hazardous Materials Safety Administration <u>Coverage</u>: All U.S. energy and hazardous materials pipelines. <u>Application</u>: All public or private pipeline system owners and operators.

Note: The U.S. Coast Guard, an agency of the Department of Homeland Security, has primary regulatory authority over U.S.-registered commercial and private watercraft.

Finally, this section identifies GPS dependencies in other critical infrastructure sectors that have a significant impact upon transportation. For example, remote crash detection systems relay their information over cellular telephone networks; however, the cellular telephone itself is reliant upon GPS time signals to synchronize and coordinate radio transmissions.

2.2. GPS Dependencies Shared by Multiple Transportation Environments and Transportation Modes

2.2.1. Overview

There are a number of systems and applications that function across multiple transportation modes that rely upon GPS positioning and/or timing data. A number of these systems are not directly transportation-based, but the services they provide directly support the safe and efficient operation of the NTS. These systems are listed in table 2-2.

Table 2-2: GPS Dependencies Shared by Multiple Transportation Environments and Transportation Modes

	Functional Purpose			User Community					Operating Environment				Operating Platform		
System or Application	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Aircraft	Infrastructure	System
Global Positioning System (GPS) Standard Positioning Service (SPS)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cargo tracking systems	X			X	X	X	X	X		X	X		X		X
COSPAS-SARSAT Program	X			X	X	X	X	X	X	X	X			X	X
Distributed networks supporting transportation system operations			X	X	X	X	X	X	X	X	X	X	X	X	X
Geo-fencing applications	X		X	X	X	X	X	X		X	X		X	X	X
NASA Satellites	X		X	X	X	X	X	X	X		X			X	X
National Spatial Reference System	X			X	X	X	X	X			X			X	
Next-Generation Radar (NEXRAD) (WSR-88D)			X	X	X	X	X	X		X	X			X	X
NOAA Environmental Satellites	X		X	X	X	X	X	X	X		X			X	X
Transportation-based analysis applications	X		X	X	X	X	X	X		X	X		X	X	X

Source: Volpe Center

2.2.2. GPS dependencies shared across multiple modes

<u>Global Positioning System (GPS) Standard Positioning Service (SPS)</u>: The GPS SPS is the primary satellite-based PNT system used by U.S. government, military and civilian users in various applications across all modes of transportation. GPS signals are used by an infinite variety of mapping and routing systems, whether using built-in (original equipment manufacturer (OEM)) devices, personal portable devices, or other equipment. There are also GPS timing receivers

that only decode the GPS signal in order to synchronize their internal clocks with the atomic clocks aboard each GPS satellite. This allows users to determine the time to within 100 billionths of a second, without the cost of owning and operating atomic clocks.[21]

Cargo Tracking Systems. Single-mode (GPS position tracking only) or dual-mode (GPS position tracking and cellular (GPRS) data transmitting) systems are used to track individual packages or consolidated freight shipments (e.g., an ISO marine shipping container). These devices are affixed to a wide variety of cargo containers carried in virtually every mode: heavy trucks, delivery vans, railcars, ocean-going ships, coastal freighters, and aircraft.[22]

COSPAS-SARSAT Program: Cospas-Sarsat is an international, humanitarian search and rescue system that uses satellites to detect and locate emergency beacons carried by ships (EPIRBs), aircraft (ELTs), or individuals (PLBs). The system consists of a network of satellites, ground stations, mission control centers, and rescue coordination centers. GPS position and timing signals are used to track the 12 satellites; GPS position data is also transmitted by certain emergency beacons.[23]

Distributed networks supporting transportation system operations: GPS time signals are used to coordinate actions of electronic and electro-mechanical devices that control safe operation of transportation systems. The specific nature of each distributed network will vary by mode, but typically involve supervisory control and data acquisition (SCADA) or other industrial control system (ICS) that monitor, control, or operate other devices. For example, within the surface highway environment, GPS-dependent systems might include electronic information signage (which rely upon GPS time signals to synchronize message displays) or toll barriers (which rely upon GPS time signals to facilitate toll collection).

Within the railroad environment, distributed networks include grade crossing barrier protection systems and track switches, while in a public transit system, they include fare barriers; each of these systems relies upon GPS timing signals to synchronize operation across the system. Other distributed systems can be found aboard merchant ships (e.g., cargo control or engine management systems) or in pipeline systems (e.g., valve actuators or pump controllers).

Geo-fencing applications (numerous): GPS position and timing data is used by a variety of "geo-fencing" applications that monitor the movements of aircraft, railcars, vessels, road vehicles and cargo containers with respect to a defined geographic boundary. Applications are used for

[21] "Timing," GPS.GOV website, available at www.gps.gov/applications/timing/, accessed August 10, 2016.
[22] For example, see "GPS Asset Tracking and Monitoring System," GPSit™ website, available at www.gpsit.com/gps-tracking-system/overview.html, accessed August 15, 2016.
[23] "Detailed Cospas-Sarsat System Description," International Cospas-Sarsat Programme website, available at www.cospas-sarsat.int/en/system-overview/detailed-cospas-sarsat-system-description, accessed August 15, 2016.

a wide variety of purposes (fleet efficiency, maintenance cycles, trucker driver hours worked, miles traveled, etc.).[24]

NASA Satellites (various): NASA operates and administers a number of satellite systems that provide close-to-real-time observations and imagery of weather, geological and meteorological phenomena; these products and services are used extensively by all transportation sector modes. GPS positioning and timing data is used to precisely determine satellite position, as well as correlate and integrate the geographic location and movement of observed phenomena.

National Spatial Reference System (NSRS): NOAA's National Geodetic Survey manages the NSRS, which provides a consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the U.S.[25] Three-dimensional GPS position data is used to determine precise locations and elevations of transportation infrastructure for all modes (i.e., airport runway elevations, locations of antennas, locations of bridges and roadways, railroad rights-of-way, boundaries of ports, etc.).

Next-Generation Radar (NEXRAD): NEXRAD (also known as WSR-88D) provides weather radar information that is used throughout the transportation system to support safe operation of all modes. NEXRAD uses GPS time signals to time-stamp and coordinate data from its network of 160 radar sites in the U.S. and overseas, to provide real-time radar coverage of weather events.[26]

NOAA Satellites (various): NOAA operates and administers a number of satellite-based programs (e.g., the Geostationary Operational Environmental Satellite (GOES)) that provide close-to-real-time observations (measurements, imagery, etc.) of weather, ocean surface heights, and other meteorological phenomena; these products and services are used extensively by all modes in the transportation sector. GPS positioning and timing data is used to precisely determine satellite position, as well as correlate and integrate the geographic location and movement of observed phenomena.[27]

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[24] For example, see "Geofencing for Improved Fleet Productivity," Advanced Tracking Technologies, Inc. website, available at www.advantrack.com/features-geofencing/, accessed August 15, 2016.
[25] "What is the National Spatial Reference System?" NOAA National Ocean Service website, available at http://oceanservice.noaa.gov/facts/nsrs.html, accessed August 15, 2016.
[26] Nita K. Patel and Robert W. Macemon, "NEXRAD Open Radar Data Acquisition (ORDA) Signal Processing & Signal Path," no date, available at https://ams.confex.com/ams/pdfpapers/70926.pdf, accessed August 15, 2016.
[27] Jennifer Ruiz and Charles Frey, "Geosynchronous Satellite Use of GPS," presentation at Institute of Navigation GNSS 18th International Technical Meeting of the Satellite Division, 13-16 September 2005, Long Beach, California, available at http://spacejournal.ohio.edu/issue9/pdf/geosynchronous.pdf, accessed August 15, 2016.

Transportation-based analysis applications (numerous): A wide variety of monitoring, modeling and analysis systems rely upon GPS positioning and time signal data to support geographic-based collection of data (e.g., emissions, regulatory compliance, etc.).[28]

2.3. GPS Use in Aviation

2.3.1. Overview

As part of its continuing mission to provide the safest, most efficient aerospace system in the world, the FAA and other Federal partners have been involved in a focused effort to improve the National Airspace System (NAS), in order to maintain U.S. leadership in global aviation, expand system capacity, ensure safety, protect the environment, and ensure national defense and homeland security throughout the NAS.[29] Many of these efforts have been focused on the Next Generation Air Transportation System (NextGen), which seeks to leverage improvements in technology to achieve the aforementioned objectives. The FAA has identified GPS PNT services as enablers of many of NextGen operating improvements, including performance-based navigation (PBN) and Automatic Dependent Surveillance Broadcast (ADS-B) services that, in turn, enable safer and more efficient flight and ground-based operations using Trajectory Based Operations (TBO), area navigation (RNAV), Required Navigation Performance (RNP), and other NextGen improvements.[30]

2.3.2. GPS Dependencies in Aviation

Table 2-3 lists GPS dependencies in the aviation environment. Note that several applications provide dual functionality in multiple environments (space, aviation, and/or surface), but

[28] For example, see "Emissions Measurement Solutions," Sensors, Inc., Saline, Michigan, available at www.sensors-inc.com/brochures/InUseServices.pdf, accessed August 15, 2016; or, Eric Gonzales, et al, "Modeling Taxi Demand with GPS Data from Taxis and Transit," Mineta National Transit Research Consortium, San José State University, available at http://transweb.sjsu.edu/PDFs/research/1141-modeling-taxi-demand-gps-transit-data.pdf, accessed August 15, 2016.

[29] "Next Generation Air Transportation System, Integrated Plan." NextGen Joint Planning and Development Office, December 2004, available at http://tg.hfes.org/astg/papers/Natl_Plan_NGATS_v5.pdf, accessed August 8, 2016. Pub.L. 108-176 (Vision 100—Century of Aviation Reauthorization Act), §710. The Next Generation Air Transportation Senior Policy Committee included the Secretary of Transportation, and representatives of the Federal Aviation Administration, National Aeronautics and Space Administration, Department of Defense, Department of Homeland Security, Department of Commerce, and the White House Office of Science and Technology Policy.

[30] "FAA APNT (Alternative Positioning, Navigation, and Timing) Update," presentation by Deborah Lawrence, Manager, FAA Navigation Programs, at the Munich Satellite Navigation Summit, March 2015, available at www.gps.gov/multimedia/presentations/2015/03/munich/lawrence2.pdf, accessed August 10, 2016.

ultimately support the operation of the NAS. These systems are in addition to GPS applications used across all modes (see section 2.1).

Table 2-3: GPS Dependencies in Aviation

System or Application	Functional Purpose			User Community					Operating Environment				Operating Platform		
	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Aircraft	Infrastructure	System
Area Navigation (RNAV)	X	X	X	X	X	X	X	X		X	X		X	X	X
Automatic Dependent Surveillance – Broadcast (ADS-B)	X	X		X	X	X	X	X		X			X		X
Digital Flight Data Recorders (DFDR)	X		X	X				X		X	X		X		
Emergency Locator Transmitter (ELT)	X			X	X	X	X	X	X	X	X		X		X
Flight Data Monitoring (FDM) systems	X		X	X			X	X		X	X		X		X
Ground Based Augmentation System (GBAS)	X	X		X	X	X	X	X		X	X		X		X
Terminal Doppler Weather Radar (TDWR)			X	X			X	X		X				X	X
Terrain Awareness and Warning System (TAWS)	X						X	X		X			X		
Universal Access Transceiver (UAT)	X		X	X	X	X	X	X		X	X		X		X
Unmanned Aircraft Systems (UAS)	X	X		X	X	X	X	X		X			X		
Wide-Area Augmentation System (WAAS)	X	X		X	X	X	X	X		X			X		X

Source: Volpe Center

Aircraft Navigation: GPS serves as the primary PNT system in modern civil aviation. Virtually all commercial aircraft are equipped with a GPS receiver, which is used in all phases of flight to determine an aircraft's position in three-dimensions, to support navigation, and provide timing signals to other avionics components. As the NAS continues to adopt Area Navigation (RNAV) practices, GPS will play a more critical role in the safe and efficient navigation of aircraft during all phases of flight. RNAV permits aircraft with space-based GPS augmentation systems (see WAAS, below) to fly user-approved routes from waypoint to waypoint, with decreased reliance on ground-based infrastructure (e.g., navigational beacons, surveillance radar). Airports equipped with ground-based GPS augmentation systems (see GBAS, below) can support reduced horizontal and vertical separation distances between aircraft, which can safely increase the number of aircraft taking off and landing.[31]

Automatic Dependent Surveillance-Broadcast (ADS-B): ADS-B is one of the critical elements of the FAA's NextGen Plan to transition from ground-based to satellite-based surveillance systems. An ADS-B-equipped aircraft determines its own position (longitude, latitude, altitude, and time) using GPS and periodically broadcasts this position and other relevant flight information (such as identification, indication of climb or descent angle, velocity, next waypoint etc.) to potential ground stations and other aircraft with ADS-B equipment.[32] ADS-B supports all phases of flight (takeoff, departure, en route, arrival, landing, and taxiing).

Digital Flight Data Recorders (DFDR): Certain aircraft are required by U.S. regulations and international treaties to carry a data recorder to aid in accident investigation. GPS provides location data and clock signal timestamps.[33] DFDR operates during all phases of flight (takeoff, departure, en route, arrival, landing, and taxiing).

Emergency Locator Transmitter (ELT): GPS position data is integrated, either internally or from an external source, into the distress signals transmitted by certain ELTs, improving the quality of information for aircraft in distress. Modern ELTs transmit signals at 406 MHz to a global network of 12 satellites. (These devices operate in a similar manner to shipboard Emergency Position Indicating Radio Beacons (EPIRBs).)

Flight Data Monitoring (FDM) systems: GPS provides positioning data and timestamps for various FDM applications, including Flight Operational Quality Assurance (FOQA), which are used to support aircraft operations, maintenance and accident investigation.[34]

Ground Based Augmentation System (GBAS): GBAS is a ground-based GPS augmentation system used for CAT-I, -II and -III precision approaches under instrument landing conditions (i.e., limited visibility). GBAS transmitters relay local differential GPS corrections to equipped aircraft over VHF frequencies (112-118 MHz). GBAS demonstrated accuracy is less than one

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[31] "GPS Applications: Aviation," GPS.GOV website, available at www.gps.gov/applications/aviation/, accessed August 10, 2016.
[32] "Automatic Dependent Surveillance-Broadcast (ADS-B)," FAA website, available at www.faa.gov/nextgen/programs/adsb/, accessed August 10, 2016.
[33] "Flight Data Recorder Handbook for Aviation Accident Investigations," National Transportation Safety Board Vehicle Recorder Division website, available at www.ntsb.gov/investigations/process/Documents/FDR_Handbook.pdf, accessed August 10, 2016.
[34] FAA Advisory Circular AC-120-82, "Flight Operational Quality Assurance," available at www.faa.gov/documentlibrary/media/advisory_circular/ac120-82.pdf, accessed August 10, 2016. See also Flight Data Services website, "A Guide to FDM/FOQA," available at www.flightdataservices.com/fdm-foqa-guide/, accessed August 10, 2016.

meter in both the horizontal and vertical axis.[35] GBAS principally supports takeoff, departure, arrival, landing, and taxiing.

Terminal Doppler Weather Radar (TDWR): TDWR is a weather radar system used primarily to detect hazardous wind shear conditions, precipitation, and upper-level winds on and near major airports throughout the U.S. TDWR uses GPS time signals to time-stamp and synchronize data from its network of 45 radar sites in the U.S. and Puerto Rico.[36]

Terrain Awareness and Warning System (TAWS): TAWS is a terrain awareness and alerting system that utilizes 3D GPS-based position data to provide terrain alerting and display functions. [37] TAWS supports all phases of flight.

Universal Access Transceiver (UAT): The UAT is an integral component of ADS-B operation, and used to transmit GPS position data to ground stations and other ADS-B-equipped aircraft and airport ground vehicles. In addition, ground based transceivers must be equipped with a GPS receiver for clock data for time synchronization.

Unmanned Aircraft Systems (UAS): Military and civil government agency operated UAS rely upon GPS for navigation for operating outside line-of-sight conditions. Civilian UAS operations are currently limited by the FAA to small aircraft (weighing less than 55 pounds). Operation is restricted to good visibility, within daytime or twilight hours, below an altitude of 400 feet, and under visual line-of-sight (VLOS) conditions.[38] Although many civilian-operated UAS are equipped with GPS receivers, the devices are used for tracking and mapping purposes, and cannot be used to navigate the UAS beyond the operator's VLOS. With civilian UAS use projected to increase significantly over the next decade, it is likely that the FAA will establish a future rule that permits operation beyond visual line-of-sight (BVLOS), which will require that UAS be equipped with GPS or another positioning system.[39]

Wide-Area Augmentation System (WAAS): WAAS is an extremely accurate space-based GPS augmentation system that supports both horizontal and vertical navigation of civil aviation.

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[35] "Satellite Navigation – Ground Based Augmentation System (GBAS)," FAA website, available at www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/laas/, accessed August 10, 2016.
[36] "Terminal Doppler Weather Radar (TDWR)," NOAA website, available at www.ncdc.noaa.gov/data-access/radar-data/tdwr, accessed August 10, 2016.
[37] FAA Advisory Circular AC-23-18, "Installation of Terrain Awareness and Warning System (TAWS) Approved for Part 23 Airplanes," June 14, 2000, FAA website, available at www.faa.gov/documentLibrary/media/Advisory_Circular/AC_23-18.pdf, accessed August 10, 2016.
[38] FAA News, "Summary of Small Unmanned Aircraft Rule (Part 107)," June 21, 2016, FAA website, available at www.faa.gov/uas/media/Part_107_Summary.pdf, accessed August 10, 2016.
[39] "Unmanned Aerial Vehicles (UAVs)–Emerging Users–Aviation GPS in UAVs," presentation by Captain Joe Burns to Space-Based Positioning, Navigation & Timing National Advisory Board, June 11, 2015, available at www.gps.gov/governance/advisory/meetings/2015-06/burns.pdf, accessed August 10, 2016.

Operated by the FAA, WAAS provides additional accuracy, integrity, and availability necessary to enable aircraft to rely on GPS for all phases of flight (departure, en route and arrival) under all meteorological conditions. WAAS is based on a network of precisely surveyed ground reference stations in the U.S.; signals from GPS satellites are analyzed to determine if any errors exist, and to assess the integrity of the system. System information and corrections data is broadcast from WAAS geostationary satellites to WAAS-enabled GPS receivers.[40]

2.4. GPS Use in Maritime Transportation

2.4.1. Overview

The maritime shipping community was one of the first to fully embrace GPS for positioning and navigation. While the high cost and sheer size of early GPS receivers was prohibitive to many land-based users, commercial shipowners recognized their value in fuel savings, through more accurate navigation and routing, and in saving lives, through more accurate positioning in the event of emergencies. Today, GPS receivers represent one of the core components of any vessel's suite of navigation and communications equipment.

Figure 2-1: Typical Marine GPS Receivers

Sources: Garmin®, Humminbird® and Koden®

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[40] "Satellite Navigation - Wide Area Augmentation System (WAAS)," FAA website, available at www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/, accessed August 10, 2016.

2.4.2. GPS Dependencies in Maritime

Table 2-4 details GPS dependencies identified in maritime transportation. These systems are in addition to GPS applications used across all modes (see section 2.1).

Table 2-4: GPS Dependencies in Maritime Transportation

System or Application	Functional Purpose			User Community					Operating Environment				Operating Platform		
	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Vessel	Infrastructure	System
Automatic Identification Systems (AIS)	X		X	X	X	X	X	X			X		X		X
Draft Information System (DIS)	X	X		X				X			X		X		X
Electronic Chart Display and Information System (ECDIS)	X	X	X	X	X	X	X	X			X		X		X
Emergency Position Indicating Radio Beacon (EPIRB)	X			X	X	X	X	X	X	X	X		X		
Global Maritime Distress and Safety System (GMDSS)	X		X	X	X	X	X	X			X		X		X
GPS Location Services for Cargo Terminal Equipment	X	X			X	X		X			X		X	X	X
Hydrographic survey systems	X			X	X	X	X	X			X		X	X	X
NOAA Vessel Monitoring System	X		X	X				X			X		X		X
Positioning Aids to Navigation (ATONs)	X			X	X	X	X	X			X			X	X
Tidal measurements	X			X	X	X	X	X			X			X	X
USACE River Information Services (RIS)	X	X		X	X	X	X	X			X		X	X	X
USACE Vessel Monitoring System	X		X	X	X	X		X			X		X	X	X
USCG Vessel Traffic Services (VTS)	X	X		X				X			X		X	X	X
Voyage Data Recorders (VDR)	X		X	X				X			x		X		
Virtual and Synthetic Aids to Navigation	X			X	X	X	X	X			X			X	X
Waterway Dredging	X	X		X	X	X		X			X		X	X	X

Source: Volpe Center

<u>Automatic Identification Systems (AIS)</u>: AIS devices transmit position and other navigation data to nearby vessels and shoreside networks using VHF radio frequencies. GPS receivers provide

AIS devices with position data (including course and speed) and time stamps. AIS improves safety of navigation, and increases maritime domain awareness for security purposes.[41]

Draft Information System (DIS): The St. Lawrence Seaway integrates GPS-based position data with highly accurate water depth information to ensure safe movement of ships operating in shallow water.[42]

Electronic Chart Display and Information Systems (ECDIS): ECDIS is a computer-based navigation system that integrates electronic navigational charts with position information from GPS or other GNSS sources, as well as data from other shipboard navigational sensors (e.g., AIS, radar, fathometer (water depth)). ECDIS is mandatory equipment for all passenger vessels over 500 GT (as of July 2014) and all cargo ships over 10,000 GT (by July 2018). The USCG and other national maritime authorities accept ECDIS devices as a replacement for conventional paper charts.[43]

Emergency Position Indicating Radio Beacon (EPIRB): GPS position data is integrated into the distress signals transmitted by certain EPIRBs, improving the quality of information from vessels in distress, thereby speeding search and recovery efforts.[44] Modern EPIRBs transmit signals at 406 MHz to a global network of 12 satellites. (These devices operate in a similar manner to ELTs found in aircraft.)

Global Maritime Distress and Safety System (GMDSS): U.S. and foreign cargo vessels are required to carry GMDSS, a suite of electronic devices that improves emergency response. GPS position data and time signals are utilized by various devices.[45]

GPS Location Services for cargo terminal equipment: GPS position and navigation data is used by automated and manual cargo-handling equipment (cranes, container carriers, etc.) to locate and transport cargo containers within cargo terminals. Data is integrated into a terminal operating system (TOS) to manage the movement of cargo into, within and out of a cargo handling facility.[46]

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[41] "Nationwide Automatic Identification System," USCG Navigation Center website, available at www.navcen.uscg.gov/?pageName=NAISMain, accessed August 10, 2016.
[42] "St Lawrence Seaway DIS Solution by TRANSAS," Maritime Professional website, July 17, 2012, available at www.maritimeprofessional.com/news/lawrence-seaway-solution-transas-226248, accessed August 10, 2016.
[43] "Charts," International Maritime Organization website, available at www.imo.org/en/OurWork/Safety/Navigation/Pages/Charts.aspx, accessed August 10, 2016.
[44] "Emergency Position Indicating Radiobeacon (EPIRB)," USCG Navigation Center website, available at www.navcen.uscg.gov/?pageName=mtEpirb, accessed August 10, 2016.
[45] "Radiocommunications," International Maritime Organization website, available at www.imo.org/en/OurWork/Safety/RadioCommunicationsAndSearchAndRescue/Radiocommunications/Pages/Default.aspx, accessed August 10, 2016.
[46] "Cargo Handling is a Hot Topic for Ports," Pacific Maritime magazine website, available at www.pacmar.com/story/2014/07/01/features/cargo-handling-is-a-hot-topic-for-ports/262.html, accessed August 10, 2016.

Hydrographic survey systems: Federal government agencies and private contractors rely upon augmented GPS signals (DGPS, which incorporates differential corrections) for determining precise locations when surveying coastlines, underwater bottom contours, features, and obstructions.[47]

NOAA Vessel Monitoring System (VMS) Program: NOAA's VMS is a satellite surveillance system primarily used to monitor the location and movement of commercial fishing vessels in the U.S. Exclusive Economic Zone (EEZ) and treaty areas. As part of NOAA's VMS program, some commercial fishermen operating in federal fisheries are required to carry and operate onboard mobile transceiver units that report vessel location and other data to NOAA Fisheries. These systems utilize GPS position data.[48]

Positioning of Aids to Navigation (ATONs): USCG, USACE, and other state and local waterway managers utilize precise augmented GPS position data (DGPS) for accurate placement of buoys, and to mark the locations of fixed aids to navigation (lighthouses, day markers, ranges, etc.), and temporary hazards. These positions are also synchronized with data incorporated into electronic chart and mapping systems.[49]

Tidal measurements: Precise, 3D GPS position data is used by NOAA to determine locations of tidal measurement stations, as well as to monitor horizontal or vertical movement of land in vicinity of those stations.[50]

USACE River Information Services (RIS): GPS position data for vessels operating on inland rivers and canals is integrated with other navigation information, such as water depth, obstructions, aids-to-navigation (ATONs) (including virtual ATONs), lock conditions, etc., as part of a comprehensive traffic management systems used to ensure safe movement of traffic.[51]

USACE Vessel Monitoring System (VMS): The U.S. Army Corps of Engineers National Dredging Quality Management (DQM) Program uses precision GPS position and time-stamp data as part of a sophisticated system to monitor and record the dredging and spoils disposal process.[52]

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47 "Differential GPS (DGPS) & Your Chart," NOAA Office of Coast Survey website, available at www.nauticalcharts.noaa.gov/nsd/DGPSchart.html, accessed August 10, 2016.
48 "Vessel Monitoring System Program," NOAA Fisheries website, available at www.nmfs.noaa.gov/ole/about/our_programs/vessel_monitoring.html, accessed August 10, 2016.
49 USCG Commandant Instruction M16500.1C, "Aids to Navigation Manual, Positioning," March 26, 1996.
50 "What is the National Spatial Reference System?" NOAA National Ocean Service website, available at http://oceanservice.noaa.gov/facts/nsrs.html, accessed August 10, 2016.
51 This system is under development; for more information see U.S. Army Corps of Engineers website, available at http://geoplatform.usace.army.mil/home/group.html?owner=k5rd9pbr&title=River%20Information%20Services%20(RIS), accessed August 10, 2016.
52 "National Dredging Quality Management Program," U.S. Army Corps of Engineers website, available at http://dqm.usace.army.mil/, accessed August 10, 2016.

USCG Vessel Traffic Services (VTS): GPS-based navigation systems are the core element of traffic management systems (operated by the USCG and in overseas ports by foreign nations) that are used to ensure safe movement of ships in areas of high-risk or high traffic (e.g., harbor approaches, narrow or shallow channels, and other restricted areas).[53]

Virtual and Synthetic Aids-to-Navigation (ATONs): The USCG and other U.S. and international maritime agencies are developing the use virtual and synthetic aids-to-navigation (ATONs) that utilize AIS technology to sends out a signal that either mimics an existing buoy, day marker, lighthouse or other physical object (synthetic ATON), or creates an ATON where there is no physical counterpart (virtual ATON). These systems rely upon GPS signals for precise positioning of virtual and synthetic ATONs.[54]

Voyage Data Recorders (VDR): Commercial cargo and passenger vessels are required by U.S. regulations and international treaties to carry a data recorder to aid in accident investigation. GPS provides location data and clock signal timestamps. [55]

Waterway Dredging: Federal government agencies and private dredging contractors rely upon augmented GPS signals for determining precise locations when dredging channels, docking areas, and other sensitive areas.[56]

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[53] "Vessel Traffic Services," USCG Navigation Center website, available at www.navcen.uscg.gov/?pageName=vtsMain, accessed August 10, 2016.

[54] B. Bleyer, "U.S. Coast Guard begins testing synthetic aids, virtual buoys," Professional Mariner, 31 July 2014.

[55] "Voyage Data Recorders," International Maritime Organization website, available at www.imo.org/en/OurWork/Safety/Navigation/Pages/VDR.aspx, accessed August 10, 2016.

[56] "Positioning Systems: Trimble Introduces Marine GPS Receiver with Two-Centimeter Vertical Accuracy," International Dredging Review website, available at www.dredgemag.com/september-october-2007/positioning-systems-trimble-introduces-marine-gps-receiver-with-two-centimeter-vertical-accuracy/, accessed August 24, 2016.

2.5. GPS Use in Surface (Ground) Transportation

2.5.1. Overview

This section describes the GPS-dependent systems or applications found within the ground-based surface modes (highway, rail and transit) used by automobiles, light trucks, heavy trucks, and wheeled or tracked transit vehicles. In many cases, all of these applications or systems can be found across all surface modes, while in other cases, use is limited to specific modes. These systems are in addition to GPS applications used in all transportation modes (see section 2.1).

2.5.2. GPS Dependencies in Highway Transportation

The greatest number of GPS receivers used in transportation can be found in U.S. road vehicles. These GPS receivers – whether a built-in, dashboard-mounted GPS navigation system, or a smartphone mapping application carried by a driver – can be found in automobiles, delivery vans, and heavy trucks operating on the 4.2 million miles of publicly-owned urban and rural interstates, arterials, collectors and local roads in the U.S.[57] Table 2-5 lists these dependencies.

Table 2-5: GPS Dependencies in Highway Transportation

System or Application	Functional Purpose			User Community					Operating Environment				Operating Platform		
	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercia	Space	Air	Surface	Subsurface	Vehicle	Infrastructu	System
Autonomous vehicles	X	X	X	X	X	X	X	X			X		X	X	X
Electronic Logging Devices (ELD)	X		X	X	X			X			X		X		X
GPS-based survey systems	X			X	X	X		X			X			X	
Intelligent Transportation Systems	X	X	X	X	X	X	X	X			X		X	X	X
Mobile platforms for Transportation Network Companies	X	X					X	X			X		X		X
Remote Crash Detection	X					X	X	X			X		X	X	X
Subsurface Utility Engineering (SUE)	X			X	X	X		X			X			X	X
Vehicle Telematics Systems	X	X		X	X	X	X	X			X		X		X
Toll Collection Systems	X		X	X	X		X	X			X		X	X	X
Tracking and routing systems	X	X	X	X	X	X	X	X			X		X		X
Truck-specific navigation systems	X	X						X			X		X	X	X

Source: Volpe Center

[57] "Public Road Length, 2014," Federal Highway Administration, Office of Highway Policy Information website, available at www.fhwa.dot.gov/policyinformation/statistics/2014/hm12.cfm, accessed August 10, 2016.

Autonomous Vehicles (automobiles, light trucks, heavy trucks): The development of autonomous vehicles (AVs) continues to accelerate in the U.S. GPS positioning and timing signals are essential elements of virtually all AV systems, since high-precision PNT data will be required for safe and efficient operation of both the AV itself and the entire roadway system.[58]

Electronic Logging Devices (ELD): Certain motor carriers and drivers are required to carry ELDs that track, manage and share records of duty status (RODS) with operators and safety officials. GPS position and time signal data are integrated with vehicle engine data and other parameters, to create a detailed record of travel.[59]

GPS-based survey systems: The FHWA's Office of Federal Lands Highway uses Real Time Kinematic (RTK) or Real Time Network (RTN) GPS augmentation techniques to survey road construction projects. Similar survey techniques are used by state and municipal transportation departments, as well as private surveyors, to design and construct roadway projects that are referenced to the common NSRS.[60]

Intelligent Transportation Systems: GPS is an essential element in the future of Intelligent Transportation Systems (ITS). ITS encompass a broad range of communications-based information and electronics technologies, including dedicated short-range communication (DSRC) between two vehicles (V2V), between a vehicle and transportation infrastructure (V2I), and between vehicles and pedestrians (V2P). Research is being conducted in the area of advanced driver assistance systems, which include road departure and lane change collision avoidance systems. These systems need to estimate the position of a vehicle relative to lane and road edge with an accuracy of 10 centimeters (4 inches).[61]

Mobile platforms for Transportation Network Companies (TNCs): TNCs (e.g., Lyft, Uber, Via, etc.) rely on accurate GPS positioning and navigation data to connect riders with carpool or rideshare opportunities, and route them efficiently to their destinations. These platforms are almost exclusively smartphone-based.[62]

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[58] Kevin Dennehy, "Autonomous Vehicles Are Coming…But When?" GPS World website, November 20, 2014, available at http://gpsworld.com/autonomous-vehicles-are-coming-but-when/, accessed August 15, 2016.
[59] "Electronic Logging Devices," Federal Motor Carriers Safety Administration website, available at www.fmcsa.dot.gov/hours-service/elds/electronic-logging-devices, accessed August 15, 2016.
[60] *Project Development and Design Manual*, Federal Highway Administration, Office of Federal Lands Highway, December 2014, Chapter 5, available at https://flh.fhwa.dot.gov/resources/design/pddm/, accessed August 15, 2016.
[61] "Roads & Highways," GPS.GOV website, available at www.gps.gov/applications/roads/, accessed August 1, 2016.
[62] Alice Wang, "The Economic Impact of Transportation Network Companies on the Taxi Industry," (2015). Scripps Senior Theses, Paper 703, p. 4, available at http://scholarship.claremont.edu/scripps_theses/703, accessed August 15, 2016.

Remote crash detection: Vehicles equipped with certain third-party subscription applications (e.g., General Motor's OnStar®, Ford's Sync®, Mercedes-Benz's mbrace®, etc.) can automatically transmit GPS position data and time-stamp to emergency services following a crash.[63]

Subsurface Utility Engineering (SUE): The FHWA encourages the use of SUE to develop reliable, detailed information concerning underground utilities. SUE is dependent upon accurate GPS position data to mark underground systems prior to construction.[64]

Telematics Systems (automobiles, light trucks, heavy trucks): Telematics is an umbrella term for a system or application that integrates GPS positioning data with data from other vehicle sensors (e.g., speed, engine data, etc.) to send, receive, and store information related to the vehicle's operation. Vehicle telematics systems—which include the dashboard, controls, and navigation systems—provide continuous connectivity to long- and short-range wireless connections. They provide a broad range of features, including some supporting safety (see "Remote crash detection," above), diagnostics (such as the ability to receive early alerts of mechanical issues), and convenience (such as hands-free access to driving directions or weather).[65]

Toll Collection Systems (various): Some open road tolling (i.e., barrier-free) collection and enforcement systems utilize GPS positioning and/or timing signals to calculate toll amounts.[66]

Tracking and routing systems: There is a wide variety of applications and systems that monitor the location and/or route of surface transportation assets (automobiles, trucks, emergency vehicles, etc.), assisting in efficient fleet dispatch, operation and management. Motor carriers utilize GPS-based tracking and routing software to maximize efficiency for route planning, reducing costs, time, and environmental emissions.[67]

Truck-specific navigation systems: GPS position data supports truck specific navigation systems include additional roadway GIS information critical to operators of commercial vehicles, such as

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[63] Remote crash detection applications are a subset of vehicle telematics systems, but are only available (as of this report) on certain passenger automobiles and light trucks (SUVs). Due to the high visibility of these systems within the consumer marketplace, these applications are highlighted separately.

[64] "Subsurface Utility Engineering," Federal Highway Administration website, available at www.fhwa.dot.gov/programadmin/sueindex.cfm, accessed August 15, 2016.

[65] Since "telematics" is the overarching term for all such systems, a number of examples of telematics systems will be discussed separately elsewhere in this document.

[66] For example, see "Toll Collection and Toll Enforcement in Free-Flowing Traffic," VITRONIC website, available at www.vitronic.com/traffic-technology/applications/tolls-and-vehicle-identification/toll-collection-and-toll-enforcement.html, accessed August 15, 2016.

[67] For example, see "Uncover your fleet's true potential," Telogis® website, available at www.telogis.com/solutions/fleet, accessed August 15, 2016.

height (e.g., bridge clearance data), weight (e.g., bridge weight limits) and other route restrictions.[68]

2.5.3. GPS Dependencies in Rail Transportation

Table 2-6: GPS Dependencies in Rail Transportation

System or Application	Functional Purpose			User Community					Operating Environment				Operating Platform		
	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Vehicle	Infrastructure	System
Amtrak Track-A-Train	X		X				X				X		X		X
Automated Track Inspection Systems (various)	X		X	X	X	X	X				X			X	X
Event Recorder			X	X	X			X			X	X	X		X
Intelligent Transportation Systems for Rail	X		X	X	X	X	X	X			X		X	X	X
Positive Train Control (PTC)	X		X	X	X	X		X			X		X	X	X
Railroad Automatic Equipment Identification (AEI) Systems	X		X					X			X		X	X	X
System Operations (Various)			X	X	X	X	X	X			X		X	X	X

Source: Volpe Center

Amtrak Track-A-Train: A consumer-oriented system for the U.S. National Railroad Passenger Corporation that uses GPS position information to track location and speed of trains, allowing riders and users to monitor train location, progress, schedule passenger pick-ups and drop-offs, etc.[69] (See https://www.amtrak.com/trainlocationmap.)

Automated Track Inspection Systems (various): Automated track inspection systems utilize GPS positioning data to locate potential problems in rail geometry, alignment, joint bar defects, etc.[70] Additional programs under development include an Ultra-Portable Ride Quality Meter (UPRQM) that incorporates GPS position and timing data with input from a tri-axis

[68] For example, see Rand McNally website, available at www.randmcnally.com/category/truck-gps, accessed August 15, 2016.
[69] "Google Helps Us Help You Track Trains," Amtrak website, available at http://blog.amtrak.com/2013/09/google-helps-track-a-train/, accessed August 15, 2016.
[70] "Track Inspection Services," ENSCO® website, available at www.ensco.com/sites/default/files/2016-06/12.0017-Track-Inspection-Services-ENSCO-Rail.pdf, accessed August 15, 2016.

accelerometer, in order to identify the location and magnitude of portions of rail infrastructure that reflect irregular track geometry or poor vertical support.[71]

Event Recorder: Certain locomotives are required by U.S. regulations to carry an event recorder to aid in accident investigation. GPS provides clock signal timestamps.[72]

Positive Train Control (PTC): PTC uses GPS for positioning data and timing signals to coordinate safe operation of passenger and freight rail systems.[73] Technology can be deployed on freight rail, commuter rail, national rail (Amtrak) and shared infrastructure. When fully deployed, PTC is expected to be implemented over a total of approximately 70,000 miles of track.[74]

Railroad Automatic Equipment Identification Systems: GPS position data is integrated with automatic equipment identification (AEI) systems to monitor and track railroad locomotives and rail cars.[75]

System Operations (Various): GPS clock data is used to synchronize railroad timing operations for scheduling, dispatch, and intermodal connections.[76]

Vehicle-to-Infrastructure (V2I) Communications Systems for Rail: Use of V2I technology is being developed to alert rail or transit vehicles and road vehicles to potential risk of collision at grade crossings and other locations. GPS positioning and/or timing data from rail and road vehicles is incorporated into the V2I system.[77]

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[71] "FRA Deploys New Ultra-Portable Ride Inspection Tool," Small Business Innovation Research program website, available at www.sbir.gov/success-story/fra-deploys-new-ultra-portable-ride-inspection-tool, accessed August 15, 2016.

[72] 49 CFR §229.135, "Event Recorders." Available at www.gpo.gov/fdsys/pkg/CFR-2012-title49-vol4/pdf/CFR-2012-title49-vol4-sec229-135.pdf, accessed August 15, 2016. See also, available at www.inspiredsystems.com.au/Rail/Asset-Protection/Locomotive-Event-Recorder.aspx, accessed August 15, 2016.

[73] "Positive Train Control (PTC) Overview: Railroad Safety," Federal Railroad Administration website, available at https://www.fra.dot.gov/Page/P0621, accessed August 15, 2016.

[74] Target deadline for full deployment is December 31, 2018 (as of August 2016).

[75] Angela Cotey, "Railroads & car-tracking technology," Progressive Railroading website, available at www.progressiverailroading.com/csx/article/Railroads-38-car-tracking-technology--25010, accessed August 15, 2016.

[76] "Civilian applications of GPS – Rail," U.S. Air Force website, available at www.losangeles.af.mil/About-Us/Fact-Sheets/Article/734556/civilian-applications-of-gps-rail, accessed August 15, 2016.

[77] "Vehicle-to-Infrastructure (V2I) Safety Applications, Concept of Operations," ITS Joint Program Office, March 2013, available at http://ntl.bts.gov/lib/48000/48500/48527/ED89E720.pdf, accessed August 15, 2016.

2.5.4. GPS Dependencies in Transit

Table 2-7: GPS Dependencies in Rail

System or Application	Functional Purpose			User Community					Operating Environment				Operating Platform		
	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Vehicle	Infrastructure	System
Intelligent Transportation Systems for Transit	X		X	X	X	X	X	X			X		X	X	X
Positive Train Control (PTC)	X		X	X	X	X		X			X		X	X	X
Transit fleet tracking and routing software	X	X		X	X	X		X			X		X		X
Transit tracker (bus, bus-rapid-transit, light rail, heavy rail)	X	X	X				X				X		X		X

Source: Volpe Center

Intelligent Transportation Systems for Transit: Use of V2I technology is being developed to alert transit vehicles and road vehicles to potential risk of collision at grade crossings and other locations. V2I transit applications can also improve traveler mobility, and incorporate environmental applications that address transit needs and priorities while providing interoperability and coexistence with connected-vehicle equipped cars and trucks.[78] GPS positioning and/or timing data from transit and road vehicles is incorporated into the V2I system: positioning data for vehicles and infrastructure, and timing data to synchronize system operations.

Transit fleet tracking and routing software: Various commercial products use GPS position data to monitor locations of transit vehicles (bus, rail, subway, paratransit, etc.) to assist transit agencies and other operators in dispatch, routing, maintenance, monitoring, etc. Systems can include geofencing capability to alert system operators when vehicles travel into or out of designated services zones.[79]

Transit tracker (bus, bus-rapid-transit, light rail, heavy rail): These consumer/rider focused systems utilize GPS position data to allow riders to track location of transit vehicles in real time.

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[78] "Transit V2I Research," Intelligent Transportation Systems Joint Program Office website, available at www.its.dot.gov/research_archives/safety/transit_v2i.htm, accessed August 16, 2016.
[79] For example, see "Fleet Type: Passenger Transportation," Teletrac® website, available at www.teletrac.com/gps-fleet-tracking/fleet-types/passenger-transport, accessed August 16, 2016.

Data is available through various mobile and desktop applications, including those developed and offered by transit agencies or those offered by third parties (using transit agency-provided location information).[80]

Positive Train Control (PTC) within Transit Systems: See discussion in section 2.5.3.

2.6. GPS Use in Subsurface Modes (Pipelines)

2.6.1. Background

GPS signals cannot penetrate below ground or below the surface of the water. Consequently, GPS technology are not used directly for PNT applications. However, GPS PNT signals are utilized in several critical ways support safe transportation of hazardous materials in the subsurface environment, specifically the vast U.S. pipeline network that moves billions of gallons or cubic feet of energy and hazardous materials each year (see figure 2-2 and table 2-8).

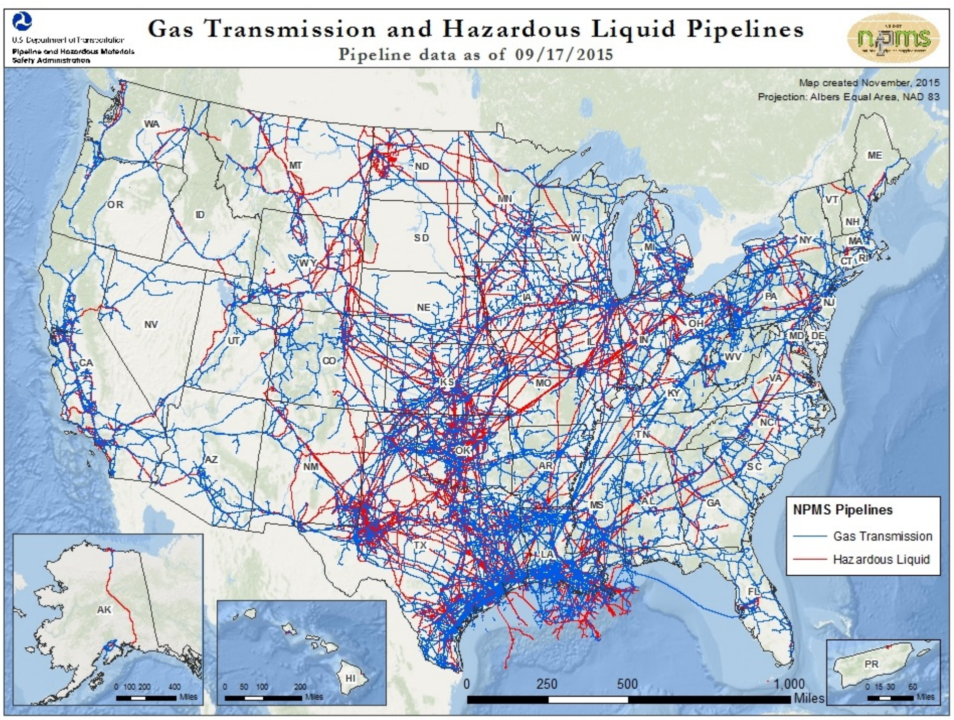

Figure 2-2: U.S. Gas Transmission and Hazardous Liquid Pipelines (2015)

Source: PHMSA (http://phmsa.dot.gov/pipeline/library/data-stats/data-visualization)

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[80] For example, see "Miami-Dade Transit Tracker iPhone and Android apps," MiamiDade.gov website, available at www.miamidade.gov/transit/transit-tracker-app.asp, accessed August 16, 2016.

Table 2-8: U.S. Regulated Pipeline and Hazardous Materials Statistics (2014)

Commodity	Capacity
Hazardous Liquids and Carbon Dioxide	199,703 miles
Natural Gas Distribution	2,189,036 miles
Gas Transmission Gathering	319,913 miles
LNG Storage Capacity	53,235,546 barrels

Source: PHMSA (http://www.phmsa.dot.gov/pipeline/library/data-stats)

2.6.2. GPS Dependencies in Subsurface Modes

GPS dependencies in the pipeline mode fall into three general categories, which are listed in table 2-9 and described below.

Table 2-9: GPS Dependencies in Subsurface Modes

	Functional Purpose			User Community					Operating Environment				Operating Platform		
System or Application	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Pipeline	Infrastructure	System
Pipeline Mapping Systems	X			X	X	X	X	X			X	X		X	X
Pipeline Management Systems			X	X				X			X	X		X	X
Pipeline Monitoring Systems	X		X	X				X			X	X	X	X	X

Source: Volpe Center

Pipeline Mapping Applications. GPS position data, including data derived from geolocation systems employing GPS augmentation techniques, are used for accurate mapping of location of surface and subsurface pipeline infrastructure – not just hazardous materials but also drinking water supply and distribution.

Pipeline Management Systems. GPS timing signals are used by data loggers to time stamp pipeline pressures, flow rates and other data used for process scheduling, control, synchronization, and monitoring for safe operation of pipelines carrying hazardous liquids, natural gas and other hazardous substances. GPS timing signals are also used to synchronize computer-based pipeline operation, monitoring and control systems.

Pipeline Monitoring Systems. Real-time GPS position data and time signals support 2D and 3D pipeline measurement and analysis of pipeline movement, integrity, stresses, etc. for purposes of operations, maintenance, and repair, to ensure safe operations. This information supplements data from pipeline-mounted inertial measurement units, in-line inspection devices (pigs), and other devices.

2.7. GPS Dependencies in Critical Infrastructure Sectors that Impact the Transportation Sector

Many other critical infrastructure sectors are also dependent upon GPS PNT signals to support safe and efficient operation. While this report did not explore those dependencies in detail, it did identify a number of examples (see table 2-10) that represent a potential and significant cascading impact upon the transportation sector in the event GPS signals are degraded or lost.

Table 2-10: GPS Dependencies in Other Critical Infrastructures that Impact Transportation

	Functional Purpose			User Community					Operating Environment				Operating Platform		
System or Application	Positioning	Navigation	Timing	Federal	State	Local	Private	Commercial	Space	Air	Surface	Subsurface	Vehicle	Infrastructure	System
Energy Sector: Power generation coordination			X	X	X	X	X	X	X	X	X	X	X	X	X
Communications Sector: Cellular telephone networks			X	X	X	X	X	X		X	X	X	X	X	X
Information Technology Sector: Internet	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Financial Services Sector: Financial systems			X	X	X	X	X	X		X	X		X	X	X

Source: Volpe Center

Energy Sector: Power generation coordination. The power grid is increasingly reliant on GPS based time signals to support phasor synchronization equipment. Failure of the power grid would have a significant cascading impact upon safety-critical functions in the transportation sector such as traffic signals, railroad switches, and grade-crossing barriers. Loss of electrical power would also impact overall operation of the transit system, stopping electric subway cars and transit vehicles, closing gas stations, and shutting down container cranes or pipelines at cargo terminal.

Communications Sector: Cellular telephone networks. Cellular telephone technology is increasingly incorporated into transportation systems, such as vehicle telematics systems or devices used by vehicle operators and pedestrians. Applications include maps, emergency alerts (e.g., OnStar®), and V2X technologies. GPS time signals are almost universally used to coordinate or synchronize operations of cellular telephone networks and switching networks, through the use of GPS disciplined oscillators.[81] Failure of the cellular communications network would have a significant cascading impact upon transportation operations, affecting safety-critical functions.

Information Technology Sector: Internet. GPS timing data is commonly used to synchronize Internet operations. In addition, data that is obtain from GPS systems (position and/or timestamp), which supports many life and safety critical transportation applications travels across the Internet. Consequently, failure of the Internet communications system would have a significant cascading impact upon transportation operations.

Financial Services Sector: Financial systems. GPS time stamps are used to synchronize and process financial transactions involving credit and debit cards. These financial instruments are used throughout the transportation system to purchase passenger tickets, book postal or freight transportation, pay roadway tolls, or purchase gasoline, natural gas or diesel fuel. Loss of the GPS timing signal could affect the financial system, which would have a significant cascading impact throughout the transportation system.

[81] National Risk Estimate, p. 29.

3. Improving the Robustness of GPS Receiver Installations

3.1. Overview

This section explores measures that GPS users in the transportation sector may employ to mitigate the risks or impact of GPS disruptions. Devices employed in the GPS user segment are comprised of two elements: the GPS antenna and the GPS receiver. Many GPS installations incorporate separate antenna and receiver units, while other GPS-equipped devices such as smartphones and GPS tracker tags combine an antenna and a receiver into a single unit. Consequently, there is a range of techniques that can be used individually or in combination to address different scenarios.

This section focuses on existing and emerging technology solutions to improve the robustness of GPS systems that are currently under study, using measures that can be employed using readily available approaches to system design, installation and operation using existing COTS technology.[82]

3.1.1. GPS Antenna Units

By the time the GPS signal transmitted from a satellite reaches earth, it is extremely weak. A typical GPS signal strength at the receiver is approximately -127.5 dBm (0.178 quadrillionth of a Watt); By comparison, a typical cell phone signal is received at -70 dBm (100 trillionth of a Watt), which represents a signal strength 562,000 times stronger than the GPS signal. The GPS signal's low power makes detection challenging, and increases its vulnerability to interference, whether through intentional jamming, ionospheric disturbances, or unintentional signals from adjacent frequency bands. Some GPS antennas must also be capable of receiving signals in multiple frequency bands. Consequently, antenna design and selection is a critical element of a robust GPS receiver system.[83]

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[82] For example, potential solutions to mitigate against intentional spoofing attacks against ADS-B and AIS systems include changing the respective signals to include authentication (see Faragher, R., MacDoran, P.F., Mathews, M.B., "Spoofing Mitigation, Robust Collision Avoidance, and Opportunistic Receiver Localisation Using a New Signal Processing Scheme for ADS-B or AIS," Proceedings of the 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2014), Tampa, Florida, September 2014, pp. 858-868, available at www.cl.cam.ac.uk/~rmf25/papers/adsb_ais_spoofing_mitigation.pdf, accessed August 25, 2016).

[83] For a detailed discussion on design characteristics of GPS antennas, see "Antennas," European Space Agency Navipedia website, available at www.navipedia.net/index.php/Antennas, accessed August 25, 2016. Also, "GPS Antennas: RF Design Considerations for u-blox GPS Receivers, Application Note," u-blox AG, p. 5. Also

Installations that allow a separate GPS antenna and GPS receiver, when compared with an integrated GPS antenna/receiver, typically allow the user a wider number of options in antenna selection, which can improve overall system robustness. The following are some measures that users can take to ensure GPS signal availability.

3.1.1.1. Proper antenna installation

The first steps that can be taken to improve robustness of any GPS antenna is to optimize installation. Ideally, the antenna's view of the sky view should be clear to the horizon within a 100 yard radius, and mounted 5 feet above any nearby reflecting surfaces, to reduce multipath (reflected) signal interference. GPS signals can be blocked or attenuated by vegetation and precipitation. In addition, the antenna should not be installed within 300 yards of any high-power transmitting antennas to prevent RF interference, particularly non-directional antennas.[84] Cable type and length must also be considered. Since many fixed antenna sites represent potential trade-offs between built infrastructure, natural foliage, and weather considerations, users should consult with a qualified installer to optimize antenna location.

These guidelines can often be followed for GPS antennas mounted on fixed transportation infrastructure, or aboard aircraft and ships. However, these measures are impractical for a moving vehicle – whether an automobile, truck, or transit vehicle – particularly when those vehicles are operating in an urban environment, where the surrounding infrastructure presents a constantly changing RF signal environment.

3.1.1.2. Install a choke ring antenna

A choke ring antenna is designed to "emphasize" signals received from satellites that transmit from elevations above the horizon of 60 degrees or more. It accomplishes this by surrounding the core antenna element with frequency-tuned concentric conductive rings, which attenuate multipath and lower elevation signals, and potential interference from signal jammers, spoofers, or other devices transmitting from ground sources at or near the same elevation as the GPS antenna. Choke ring antennas can be open (see figure 3-1) or enclosed in a protective radome. The inherent

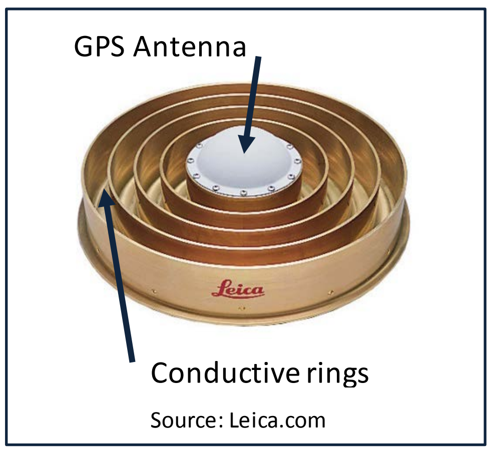

Figure 3-1: Choke Ring Antenna

[84] Federal modal transportation agencies may issue regulations that specify antenna installation requirements that apply to specific modes.

disadvantage of the choke ring design is that attenuating lower-elevation signals can also lower the number of tracked satellites and reduce the signal strength of legitimate GPS signals.[85] Choke ring antennas are also heavier than some other antenna designs, due to the associated ring structure.

3.1.1.3. *Install a resistive plane antenna*

A resistive plane antenna uses electrical resistance (rather than physical, frequency-tuned choke rings) to keep unwanted signals from reaching the central antenna element. Signals received by the resistive plane dissipate energy, thereby reducing or eliminating interference. Resistive plane antennas provide similar performances as choke ring antennas, but with less weight and cost.

3.1.1.4. *Install an anti-jamming antenna*

There are a variety of anti-jamming antenna technologies available. These include selective nulling antennas,[86] adaptive nulling antennas,[87] and multi-element, controlled radiated pattern antennas.[88] These devices use various passive or active technologies to detect and filter out illegitimate (jamming) signals from the legitimate GPS signals sent to the GPS receiver. These devices can often be retrofitted to existing installations, but may require an additional source of power.

3.1.2. GPS Receiver Units

3.1.2.1. *Maximize the number of GPS satellites used to fix a position*

GPS receivers must track a minimum of four satellites in order to obtain accurate data for positioning and navigation (PN) in three dimensions: latitude (north/south) and longitude (east/west), and altitude. A signal from a single satellite is needed to provide timing (T) data. Some receivers require information from five or more satellites, to support aviation safety-of-

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[85] Waldemar Kunysz, "A Three Dimensional Choke Ring Ground Plane Antenna." NovAtel, Inc., no date, available at http://gps-ttff.tripod.com/3D.pdf, accessed August 30, 2016.
[86] Frank Bauregger, Todd Walter, Dennis Akos and Per Enge, "A Novel Dual-Patch Anti-Jam GPS Antenna," Presented June 2002 at the Institute of Navigation's Annual Meeting, Albuquerque, New Mexico, available at http://gps.stanford.edu/papers/Bauregger_IONAM_2002.pdf, accessed August 30, 2016.
[87] "GAJT-710ML Anti-Jam Antenna, Specifications," NovAtel website, available at www.novatel.com/products/gnss-antennas/gajt-anti-jam-antennas/gajt/, accessed August 30, 2016.
[88] Frederic Leveau, Solene Boucher, Erwan Goron, and Herve Lattard, "Conception, Realization, Evaluation of a Seven-Element GNSS CRPA," GPS World website, February 1, 2013, available at http://gpsworld.com/anti-jam-protection-by-antenna/, accessed August 30, 2016.

life applications.[89] However, while there can be six or more satellites visible to the receiver's antenna at any time, the geometry of the satellite constellation–where the satellites are in relationship to the receiver—has a direct impact on the quality of the position solution estimated by the receiver.

Satellites that are directly above or well above the horizon typically provide more precise location data, when compared to satellites that are low to the horizon. GPS receivers are designed to analyze the visible satellites and select the combination of satellites that are likely to give the greatest precision. Furthermore, GPS satellites are in constant motion, as they rise above the horizon, move across the sky and disappear from view. Consequently, a GPS receiver must have sufficient computing power to constantly assess and monitor the changing satellite constellation.

Some GPS receivers track as few as 12 satellites, while more advanced satellite receivers can track virtually any satellite that comes into view, whether from the U.S. GPS or another GNSS constellations. **To increase robustness of PNT capability, users may consider a GPS receiver capable of tracking the highest number of satellites.**

3.1.2.2. Use a multi-frequency GPS receiver

GPS satellites transmit on multiple frequencies, with older satellites transmitting on two frequencies (L1 and L2) and newer satellites transmitting on three frequencies (L1, L2 and L5). The specific signals and frequencies available for civilian use are listed in table 3-1.

Table 3-1: Civilian GPS Signals (Current and Planned)

Signal	Center Frequency	Notes
L1 C/A (Coarse Acquisition)	1575.42 MHz	The most commonly used civilian GPS signal. Commonly called the "legacy signal."
L1C (Civilian)		Allows interoperability with some other GNSS signals (e.g., Galileo, Beidou). Signal design improves mobile GPS reception in cities and other challenging RF environments
L2C (Civilian)	1227.6 MHz	Higher effective power than L1 C/A
L5	1176.45 MHz	Higher effective power than L1 C/A

Source: Volpe Center, www.gps.gov

[89] Homeland Security Systems Engineering and Development Institute, "GPS Critical Infrastructure Risk Mitigation Techniques: Final Report," Department of Homeland Security, Washington, 2011, p. 6.

Within each designated frequency, GPS satellites transmit multiple coded signals. Some coded signals are intended for military purposes only, and can only be decoded by specially-configured military GPS receivers. Other signals are broadcast at a higher power, making them easier to receive under trees and even indoors. The use of multi-frequency receivers mitigates against several potential GPS disruptions:

- Single frequency jamming
- Single frequency spoofing
- Spectrum encroachment (provided that only one GPS frequency is affected by adjacent band interference)
- Certain space weather

According to GPS.GOV, certain multi-frequency combinations provide distinct benefits to the user:[90]

L1 C/A and L2C dual band: When combined with L1 C/A in a dual-frequency receiver, L2C enables ionospheric correction, a technique that boosts accuracy. Users with dual-frequency L1-C/A and L2C receivers will experience faster signal acquisition, enhanced reliability, greater operating range, and high precision.

L1 C/A and L5 dual band: The L5 signal is broadcast in a radio band reserved exclusively for aviation safety services, and features higher power, greater bandwidth, and an advanced signal design. Once a full constellation of Block III satellites transmitting the L5 signal is operational (estimated in 2024), aircraft will be able to use L5 in combination with L1 C/A to improve accuracy, via ionospheric correction, and robustness, via signal redundancy.

L1 C/A, L2C and L5 tri-band: Tri-band receivers are capable of providing highly robust positioning service. Units that use three GPS frequencies often employ a technique called "trilaning," which may allow sub-meter accuracy without augmentations, and very long range operations with augmentations such as WAAS and SBAS.[91]

However, some GPS receivers, particularly small form-factor devices such as smartphones or tracking tags, may only be configured with a single-frequency receiver and built-in antenna. **To improve robustness, users can consider deploy a multi-frequency GPS receiver.**

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[90] "New Civil Signals," GPS.GOV website, available at www.gps.gov/systems/gps/modernization/civilsignals/, accessed August 24, 2016.
[91] Irving Leveson, "Benefits of the New GPS Civil Signal: The L2C Study," *Inside GNSS*, July-August 2006, available at www.insidegnss.com/pdf/08-leveson-v5Web.pdf, accessed August 24, 2016.

3.1.2.3. Use a multi-system GNSS receiver, capable of tracking satellites from two or more GNSS satellite constellations

While the U.S. GPS provides global coverage available to U.S. and international users, other nations have developed and deployed their own satellite-based navigation systems. The GNSS constellations presently deployed are shown in table 3-2.[92]

Table 3-2: Global Navigation Satellite Systems Currently Deployed (2016)

System	Deployed by	Coverage
Beidou	China	Global
Galileo	European Union	Global
GLObal NAvigation Satellite System (GLONASS)	Russian Federation	Global
Global Positioning System (GPS)	United States	Global
Indian Regional Navigation Satellite System (IRNSS)	India	Regional

Source: Volpe Center

Some systems are interoperable (i.e., satellites share compatible signals, frequencies, etc.), while others are entirely independent. These characteristics offer significant advantages in a multi-system GNSS receiver:

- Reduced reliance on space and ground segment infrastructure of a single GPS network.
- Increased potential number of tracked satellites. Some multi-GNSS constellation receivers have been shown to track over 190 different signals in a six-hour period.[93]
- Reduced susceptibility to single-frequency interference, whether from intentional jamming or spoofing, or due to unintentional adjacent band transmissions.
- Reduced susceptibility to certain space weather events (ionospheric effects tend to be stronger at lower frequencies (e.g., L2C and L5 signals are located).[94]

Manufacturers offer hundreds of models of multi-GNSS constellation receivers to choose from, for a wide variety of fixed and mobile transportation applications.[95]

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[92] Japan's Quasi-Zenith Satellite System (QZSS) is a regional GNSS currently being deployed intended to be integrated with, and complementary to, the U.S. GPS. However, it is not currently envisioned as a fully independent system. For more information, see QZSS website, available at http://qzss.go.jp/en/index.html, accessed August 30, 2016.

[93] Don Jewell, "In defense of PNT: Multi-GNSS to the rescue," GPS World website, available at http://gpsworld.com/in-defense-of-pnt-multi-gnss-to-the-rescue/, accessed July 29, 2016.

[94] "Satellite Navigation & Space Weather: Understanding the Vulnerability & Building Resilience," Policy Workshop Report, American Meteorological Society, March 2001, p. 8, available at www.ametsoc.org/ams/assets/file/spacwx_gps_2010.pdf, accessed August 24, 2016.

[95] "GPS World, Receiver Survey 2016," GPS World website, available at http://gpsworld.com/wp-content/uploads/2012/10/GPSWorld_2016ReceiverSurvey.pdf, accessed August 30, 2016.

Multi-GNSS Systems provide protection against spoofing attacks. Civilian GPS signals are not encrypted.[96] Consequently, they are subject to potential spoofing attacks in which an adversary or attacker transmits false GPS signals in order to deceive the GPS receiver into determining a false position and/or time. However, the use of a multi-constellation GNSS receiver that can track multiple GNSS constellations can be effective against spoofing attacks, because an adversary would have to produce and transmit all possible GNSS signals simultaneously to spoof the target receiver. (This assumes that the multi-GNSS receiver has internal algorithms that enable it to evaluate all incoming signals, and then ignore spoofed signals when determining position or time.) The incorporation of an internal measurement unit (IMU) (see following section) in the GPS receiver system can bring an added measure of spoofing detection and protection, since the Earth's gravitational field or vehicle dynamics cannot be spoofed in such a manner so as to fool the IMU into thinking that it has moved when it has not.[97]

3.1.2.4. Use of GPS Augmentation Services

GPS augmentations are services that improves the accuracy, availability or reliability of GPS by integrating additional data into the GPS calculation. Data provide corrections for atmospheric conditions, changes in satellite position, or other errors affecting GPS calculations. Systems deployed in the U.S. include the Wide Area Augmentation System (WAAS) and the Ground-Based Augmentation System (GBAS) (both maintained by the FAA), NOAA Continuously Operating Reference Stations (CORS)[98] and the Global Differential GPS System (maintained by NASA).[99]

GPS augmentation systems improve the robustness of GPS receivers to certain GPS disruptions by providing correction information that mitigates their impact. For example, corrections could account for mild space weather disturbances to the ionosphere, or for atmospheric conditions based upon satellite elevation. Satellite-based augmentation systems (SBAS) in particular offer benefits that improve robustness in a multi-system augmented GPS receiver. SBAS currently deployed are shown in table 3-3, with a global coverage map shown in figure 3-2.

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[96] GPS satellites do transmit encrypted military signals that can only be processed by specially-equipped GPS receivers on available to the U.S. Armed Forces and other Federally-authorized users.

[97] "Understanding the Difference Between Anti-Spoofing and Anti-Jamming," Novatel website, available at www.novatel.com/tech-talk/velocity/velocity-2013/understanding-the-difference-between-anti-spoofing-and-anti-jamming/, accessed August 30, 2016.

[98] "Continuously Operating Reference Station (CORS)," NOAA website, available at www.ngs.noaa.gov/CORS/, accessed August 24, 2016.

[99] "Global Differential GPS (GDGPS) System," NASA Jet Propulsion Laboratory, available at www.gdgps.net, accessed August 24, 2016.

Table 3-3: Operational Space-Based Augmentation Systems (2016)

System	Deployed by	Status
Wide Area Augmentation System (WAAS)	U.S.	In service
Multi-functional Satellite Augmentation System (MSAS)	Japan	In service
European Geostationary Navigation Overlay Service (EGNOS)	European Union	In service
GPS Aided Geo Augmented Navigation (GAGAN)	India	In service
System for Differential Corrections and Monitoring (SDCM)[100]	Russia	Under development

Source: Volpe Center

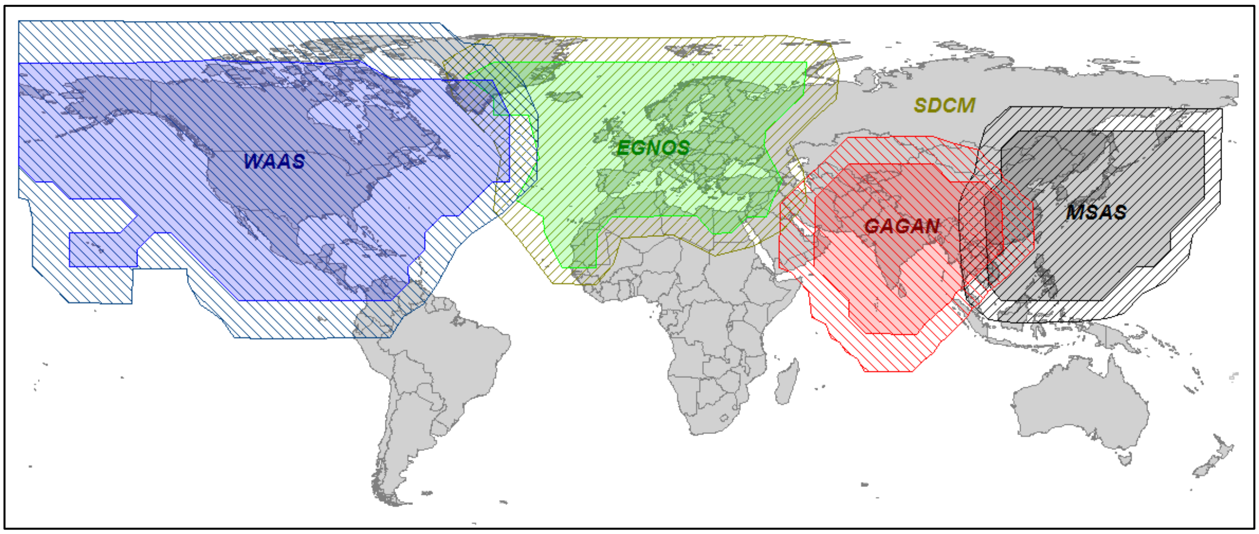


Figure 3-2: Coverage Map of Operational Space-Based Augmentation Systems (2016)

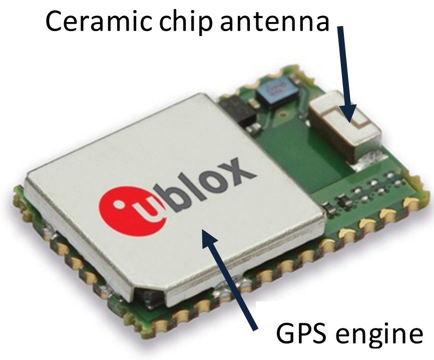
Source: Geneq, Inc. www.sxbluegps.com

Today, multi-GNSS systems, when combined with SBAS, show some improvement in penetrating dense canopies and urban canyons by virtue of their higher numbers of satellites, and the dispersed geometry available through use of multiple satellite constellations. Many GPS receivers are capable of processing SBAS system information for multiple GNSS constellations, which can increase robustness of GNSS PNT operations in parts of the world where SBAS services are available.

[100] SDCM is currently designed as an SBAS to both GPS and GLONASS, whereas other systems (WAAS, EGNOS, GAGAN, and MSAS) currently augment only GPS signals.

3.1.3. Integrated GPS Antenna-Receiver Devices

Most devices with integrated GPS receiver-antenna systems (e.g., personal GPS mapping/trekking devices, smartphones, cargo tracking tags) employ tiny ceramic "patch antennas" fitted to a circuit board and connected to a GPS receiver "engine." The entire unit measures only 0.38 x 0.55 x 0.08 inches (see figure 3-3).[101] These units provide reliable, cost-effective performance in a wide variety of applications.



Source: ublox.com

Figure 3-3: Typical GPS Module

However, due to their inherently small form factor and installation into multi-purpose RF devices, many of these devices cannot incorporate some of the features that improve resistance to interference that might otherwise be available in stand-alone GPS antennas and receivers. There are other practical considerations and trade-offs when designing a GPS antenna and receiver system that will be integrated with other RF devices into a small, portable device such as a cell phone, where space, weight and power consumption are critical.[102]

However, due to the increasing concern with GPS disruptions, a number of manufacturers have begun developing robust devices with a smaller form-factor, such as multi-system GNSS cargo trackers,[103] and small anti-jamming antennas (see figure 3-4). Further developments in this area are expected.

Source: Mayflower Communications

Figure 3-4: Small Anti-Jamming GPS Antenna

[101] "CAM-M8 Series: product specifications," available at www.u-blox.com/en/product/cam-m8-series, accessed August 25, 2016.

[102] Richard B. Langley, "Innovation: Mobile-Phone GPS Antennas." GPS World website, February 1, 2010, available at http://gpsworld.com/professional-oemcomponent-technologiesinnovation-mobile-phone-gps-antennas-9457/, accessed August 31, 2016.

[103] For example, see "Blue Sky Network HawkEye 7200," Blue Sky Network website, available at http://blueskynetwork.com/product/hawkeye-7200/, accessed August 31, 2016.

3.1.4. Considerations for GPS-based Time and Frequency Systems

GPS devices used for timing and frequency systems (TFS) incorporate a GPS antenna and receiver that process GPS signals to determine a precise time; that information is then utilized by other systems to synchronize operations. The U.S. Department of Homeland Security Computer Emergency Readiness Team (US-CERT) has identified a number of best practices to select, install, operate and monitor fixed TFS.[104]

- Receiver selection: There is a wide selection of commercially available GPS timing receivers that provide a variety of GPS-based timing solutions.[105] These include:
    - GPS time receivers, determine time directly from GPS signal;
    - GPS disciplined oscillators that use GPS timing signal to update an internal oscillator; or,
    - OEM (original equipment manufacturer) modules and circuit board products, which are GPS receiver components that can be incorporated into other devices.
- Antenna placement: See section 3.1.1.1.
- Antenna selection: Most fixed GPS TFS systems will incorporate a fixed radiation pattern antenna (FRPA), which provides basic protection against interference from out-of-band frequencies, but little protection against intentional interference (jamming). For installations that are highly sensitive to potential disruptions, consider installing an anti-jamming antenna, such as a choke ring or an anti-jamming antenna (see section 3.1.1).
- Initialization: Allow sufficient time for the GPS receiver to complete initialization. Many high-precision timing applications can take up to 12 hours from start-up to achieve specified performance levels. Users must consult the device documentation or manufacturer's specifications for initialization times.
- Outages: during a GPS outage or interference event, a TFS may revert to a secondary, back-up timing source. This secondary source must be the same accuracy as GPS, or have sufficient holdover time to meet the operational needs of the installation for the expected operational scenario outages. Once GPS signals are restored, it may take several hours to return to specified performance levels. Users should monitor the device's Time and Frequency Distribution Unit (TFDU) for reference source switching.

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[104] "Best Practices for Improved Robustness of Time and Frequency Sources in Fixed Locations," Department of Homeland Security Computer Emergency Readiness Team, 6 January 2015, available at https://ics-cert.us-cert.gov/sites/default/files/documents/Best%20Practices%20-%20Time%20and%20Frequency%20Sources%20in%20Fixed%20Locations_S508C.pdf, accessed August 31, 2016.

[105] The National Institute for Science and Technology maintains a list of manufacturers of commercially-available time and frequency receiver products, available online at www.nist.gov/pml/div688/grp40/receiverlist.cfm, accessed August 31, 2016.

- Monitor GPS alarms: most TFS devices alert users when a GPS signal is lost and the device goes into holdover mode; users must monitor these alerts and take appropriate action.

3.1.5. Other Best Practices for GPS-based PNT systems.

System operators and individual GPS users can take a number of other steps to mitigate potential disruptions of GPS-based PNT systems:

- Optimize installation of antenna and receiver, and seek expertise for installation as necessary.
- Follow manufacturer's requirements and recommendations for installation, operation, and maintenance of GPS equipment, including initialization, restart, and routine monitoring.
- Once equipment is installed, follow best practices for your specific application. For example:
  - "Best Practices in Geographic Information Systems-Based Transportation Asset Management"[106]
  - "Best Practices In Regional, Multiagency Traffic Signal Operations Management"[107]
- For networked GPS equipment (whether using a local area network or through the Internet), follow best practices for computer network systems and system security. This will mitigate the risk of malicious spoofing of GPS PNT signals. For example:
  - NIST "Cybersecurity Framework"[108]
  - US-CERT "Best Practices to Protect You, Your Network, and Your Information" [109]
- Notify the appropriate authorities of any suspected degradation, disruption, or anomaly involving GPS. Although the U.S. Government continuously monitors GPS, individual users are often the first to notice a potential anomaly, such as an area of consistently lost satellite coverage. The following resources are available to users 24 hours a day:
  - For civil and commercial non-aviation users (highways, railways, waterways): USCG Navigation Center: http://www.navcen.uscg.gov/?pageName=gpsUserInput
  - For civil and commercial aviation users: Federal Aviation Administration: http://www.faa.gov/air_traffic/nas/gps_reports/

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[106] John A. Volpe National Transportation Systems Center, "Best Practices in Geographic Information Systems-Based Transportation Asset Management," Federal Highway Administration, January 2012, available at www.gis.fhwa.dot.gov/documents/gis_assetmgmt.pdf, accessed August 30, 2016.
[107] "Best Practices in Regional, Multiagency Traffic Signal Operations Management," Scan Team Report, National Cooperative Highway Research Project 30-68A, Scan 07-04, available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/nchrp20-68a_07-04.pdf, accessed August 30, 2016.
[108] Available at www.nist.gov/cyberframework/, accessed August 31, 2016.
[109] Available at www.us-cert.gov/ncas/current-activity/2015/07/31/Best-Practices-Protect-You-Your-Network-and-Your-Information, accessed August 31, 2016.

- o For military users: Schriever Air Force Base, 50th Space Wing https://gps.afspc.af.mil/index.html (link may not work for non-military users)

The DHS NRE identified four areas of uncertainty that impact the risks of GPS disruptions on critical infrastructure sectors, including the transportation sector:[110]

- The vulnerability of GPS to intentional or unintentional disruptions.
- The extent to which GPS disruptions can be identified and mitigated.
- The extent to which GPS-based applications are layered into sector operations.
- The accuracy, availability, integrity, and continuity of alternative PNT systems available to provide robustness.

A system operator has greatest control over the last two: understanding where GPS-based applications are located within their own system, and ensuring that an alternate source of PNT data is integrated into the system design. The DHS NRE further identified the following mitigation techniques.[111]

> *To mitigate a potential GPS disruption with high consequences, regulations—including technology import controls—should keep apace of advancements in GPS-enabled technology applications. Standardization and/or regulation of GPS receivers—e.g., technical characteristics and software—could mitigate future risks. Also essential is implementing a GPS backup system or PNT alternatives.*
>
> *Ensuring that receivers are capable of receiving signals from other systems in addition to GPS would allow some backup capability. The well-established presence of an effective backup would discourage a jamming attack on GPS in the first place. Furthermore, improving signal integrity monitoring, developing a suite of sensors that can detect and characterize interference, and establishing a single processing and repository site to capture information on GPS disruption incidents across the United States would allow for more accurate risk assessments in the future. Finally, the ongoing effort to harden GPS user equipment against jamming and spoofing should be encouraged, and the Department of Homeland Security (DHS) Office of Infrastructure Protection's draft GPS Risk Mitigation Techniques and Programs Report provides more details on mitigation measures.*

[110] National Risk Estimate, op cit., p. 6.
[111] National Risk Estimate, op cit., pp. 5-6.

4. Alternative Solutions for PNT Data

A GPS disruption incident will have long-term implications for the Transportation Systems Sector as operations become more dependent on GPS. Prudent system engineering will ensure the development of appropriate architectures that do not rely overly on GPS for PNT by providing alternate non-GPS-dependent means.[112]

4.1. Overview

GPS users worldwide have experienced disruptions and will continue to do so. Whether these disruptions are intentional or unintentional, environmental or manmade, they represent an ongoing set of threats to GPS-dependent systems. The U.S. government is responsible for developing both existing and new technologies to serve as backup or alternate sources of PNT data.[113] This backup or alternate capability can serve as a substitute for core GPS PNT services, as well as serve as an independent means to crosscheck and verify GPS-derived PNT information, which is a key mechanism to detect GPS spoofing. This section will evaluate current technologies that might be utilized for alternative PNT services.

The following analysis explores the potential suitability for various alternative solutions in specific modal applications. For this report, the surface operating environment used by road vehicle (e.g., automobiles, trucks, motorcoaches) was broken down into two different sub-environments (highways and local roads), since the built infrastructure and other characteristics of open highways can be significantly different from that found on local or urban roads.

4.2. Alternative Positioning and Navigation Solutions

This section identifies alternative positioning and navigation solutions currently in use that might be expanded for broader use beyond current applications (see table 4-1). These include both existing systems and technologies, as well as systems under review and evaluation.

[112] National Risk Estimate, p. 5.
[113] "National Positioning, Navigation, and Timing Architecture Implementation Plan, April 2010," available at http://ntl.bts.gov/lib/34000/34500/34508/2010_national_pnt_architecture_implementation_plan_and_memo_for_public_release.pdf, accessed August 25, 2016.

Table 4-1: Alternative Systems Available for Positioning and Navigation

System or Application	Potential System Coverage: Space	Global	Regional	Local	Position Accuracy: >100m	100-50m	50-10m	10-1m	<1m	Potential Suitability for Modal-Specific Applications: Aviation	Maritime	Highways	Local Roads	Railroads	Transit	Pipelines
Baseline: Global Positioning System (GPS) Standard Positioning Service (SPS)	Purple	Purple	Purple	Purple	Green	Green	Yellow	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Multi-Constellation Global Navigation Satellite System	Purple	Purple	Purple	Purple	Green	Green	Yellow	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
GPS Plus Augmentation			Purple	Purple	Green	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Green
eLoran (Enhanced Long Range Aid to Navigation)			Purple	Purple	Green	Green	Green	Yellow	Red	Yellow	Green	Yellow	Red	Red	Red	Yellow
Nationwide Differential GPS (NDGPS)			Purple	Purple	Green	Green	Yellow	Yellow	Red	Yellow	Green	Yellow	Yellow	Red	Yellow	Yellow
Locata®				Purple	Green	Green	Green	Green	Green	Red	Red	Yellow	Yellow	Yellow	Yellow	Red
Cellular telephony LTE (Long-Term Evolution)				Purple	Green	Green	Red	Red	Red	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow
Inertial Navigation System (INS) or Inertial Measurement Unit (IMU)				Purple	Yellow	Red	Red	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
VHF Omnidirectional Range (VOR) and Distance Measuring Equipment (DME) (VOR/DME)				Purple	Green	Yellow	Red	Red	Red	Yellow	Yellow	Red	Red	Red	Red	Red
LIDAR/Optical				Purple	Green	Green	Green	Green	Green	Red	Red	Red	Yellow	Red	Red	Red
Integrated Multi-Sensor		Purple	Purple	Purple	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow

Source: Volpe Center, using data from DOT Office of Position, Navigation and Timing

KEY TO TABLE 4-1

Potential System Coverage

Space	System can be used in space (above 100 kilometers)
Global	System appears capable of providing world-wide service
Regional	System appears capable of meeting modal applications at a regional level (i.e., large metropolitan area, an entire state, a river system, or a multi-state network)
Local	System appears capable of meeting modal applications at the local level (i.e., a city, port, airport, terminal, etc.)

Position Accuracy

Green	System meets the stated performance standard.
Yellow	System usually meets the performance standard, but under certain circumstances, it might not.
Red	System does not meets the performance standard.

Suitability for Potential Modal-Specific Applications

(green)	System appears capable of meeting all positioning and navigation requirements for the specific modal application
(yellow)	System appears capable of meeting many, but not all of the critical positioning and navigation requirements for the specific modal application
(red)	System is incapable of meeting the most critical positioning and navigation requirements for the specific modal application

4.2.1. Multi-Constellation Global Navigation Satellite System (GNSS)

As discussed previously, a multi-constellation GNSS system can track satellites from two or more independent GNSS constellations (e.g., GPS, Beidou, GLONASS, Galileo, etc.). This mitigation approach reduces reliance on a single GNSS network and its associated infrastructure, which improves robustness and resilience. This approach also allows use of existing COTS technology, with numerous commercial products currently available.[114] Multi-GNSS systems can also provide coverage in all operating environments (space, aviation, marine, surface, and pipelines).

However, not all GNSS satellite constellations provide global coverage; for example, the Beidou system coverage is focused on China and the Western Pacific Ocean, while India's IRNSS satellites provide coverage only within approximately 1,500 kilometers of India's borders.[115]

This approach may not adequately mitigate impact of radio frequency-based disturbances, particularly jamming, space weather, and spectrum encroachment, since GNSS satellites operate in the same frequency bands, with some systems sharing the same radio frequencies. Some protection could be provided against intentional spoofing, since the signal and coding designs vary from GNSS system to system, making it more difficult to carry out an attack against multiple GNSS systems.

4.2.2. GPS with Augmentation

As discussed in a previous section, GPS augmentation systems (both ground-based and space-based) improve the robustness of GPS receivers to certain GPS disruptions by providing correction information that can mitigate disruptive impacts. Although this approach relies upon the underlying GPS technology (signal strength, frequencies, etc.) – and its vulnerabilities, the

[114] "GPS World, Receiver Survey 2016," op cit.

[115] "Indian Regional Navigational Satellite System," Earth Observation Portal website, available at https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/irnss, accessed August 25, 2016.

use of GPS with augmentation might otherwise improve the reliability of GPS PNT services under challenging conditions that could render basic GPS PNT services unsatisfactory.

4.2.3. eLoran

Enhanced Long Range Aid to Navigation (eLoran) is a proposed technology upgrade of the original LORAN-C system in service from the 1950s until 2010. LORAN is a hyperbolic radionavigation system that determines a position from the intervals between signal pulses received from widely spaced, ground-based transmitters. One of LORAN's strengths lies in its low frequency (100 kHz) and high radiated power (from 100 to 1,000 Watts); intentional jamming would require significant infrastructure – including transmitting antennae nearly 200 meters tall – which would be difficult to hide.[116]

eLoran incorporates significant enhancements to receiver design and transmission characteristics that increase the accuracy and usefulness of the original LORAN-C system.[117] DHS, USCG and two private firms entered into a three-year cooperative research and development agreement in May 2015 to test and demonstrate eLoran concepts utilizing existing LORAN-C sites.[118] There have been numerous Federal legislative initiatives to restore and upgrade this service as eLoran; however, as of the date of this report, no definitive action has been taken to establish eLoran services.[119]

4.2.4. Nationwide Differential GPS (NDGPS)

The Nationwide Differential GPS (NDGPS) service is a ground-based GPS augmentation system that broadcasts correction signals on radiobeacon frequencies, which are used to improve the accuracy and integrity of GPS-derived positions. (The current NDGPS service is implemented through agreements between multiple Federal agencies including USCG, DOT, and USACE.) Once envisioned as a large-scale national augmentation system with nearly 90 transmission sites providing coverage along the U.S. East, West and Gulf coasts and throughout the inland river system, NDGPS has proven less successful, due to improvements in GPS accuracy (e.g.,

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[116] "eDLoran: The Next-Gen Loran," GPS World website, June 28, 2014, available at http://gpsworld.com/edloran-the-next-gen-loran/, accessed July 25, 2016.
[117] See "Benefit-Cost Assessment Refresh: The Use of eLoran to Mitigate GPS Vulnerability for Positioning, Navigation, and Timing Services," John A. Volpe National Transportation Systems Center, November 5, 2009, available at https://rntfnd.org/wp-content/uploads/Benefit-Cost-of-eLoran-Volpe-Center-2009.pdf, accessed August 31, 2016.
[118] "Contract Supports New Tests of eLORAN as GPS, PNT Backup," Inside GNSS website, May 22, 2015, available at www.insidegnss.com/node/4504, accessed August 30, 2016.
[119] Section 610 of Public Law 114-120 (the Coast Guard Authorization Act of 2015) directed the Secretary of Homeland Security to halt the dismantling of existing LORAN-C infrastructure pending a determination that the infrastructure was not needed "…to provide a positioning, navigation, and timing system to provide redundant capability in the event the Global Positioning System signals are disrupted."

elimination of selective availability of GPS signals) and through the development of satellite-based augmentation systems (e.g., WAAS). As of 2016, only 46 remote NDGPS broadcast sites remain in service.[120]

This approach envisions repurposing existing NDGPS infrastructure to create an alternative PNT system. Options being considered include: a) creating a ground-based constellation of GPS transmitters (pseudolites) that could be used by existing GPS receivers for PNT purposes; b) use of existing infrastructure to transmit GPS-based timing signals only; or, c) to serve as eLoran sites (to fill coverage gaps, transmit timing signals, etc. of that system).

If the ground-based, pseudolite approach is taken, it will allow continued use of existing GPS hardware, and will operate in a nearly identical manner to the current GPS system. However, since it relies upon many components and characteristics of the existing GPS, it will continue to be subject to the same potential disruptions, though perhaps to a lesser degree. Furthermore, land-based transmitters may not provide adequate coverage of oceanic areas. If the NDGPS infrastructure is used in some other manner (e.g., to augment any future eLoran system), the exact nature, scope and cost of that system is unknown at this time.

4.2.5. Locata®

Locata® is a positioning system and proprietary technology that uses a ground-based array of transmitters and specially configured receivers to determine a position relative to a geographic reference point. The Locata® system has proven itself accurate in several operating environments, but as of 2016, it has not been fully evaluated across the full spectrum of transportation environments.

Locata® operates in a similar manner to existing GPS technology: they are both direct sequence spread spectrum signals; receivers for both systems give pseudorange and carrier-phase measurements; both systems can use the pseudorange or carrier phase for positioning; and, precision and accuracy is comparable.[121]

However, Locata® transmits using radio frequency spectrum in an unprotected, open-access band (2.4 GHz industrial, scientific and medical (ISM)), which precludes its use for safety or security applications.[122] The Locata® system also employs ground based antennas; while ground-based devices are easier to maintain and replace, deployment over large geographic

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[120] "NDGPS General Information." USCG Navigation Center website, available at www.navcen.uscg.gov/?pageName=dgpsMain, accessed August 8, 2016.
[121] "How is Locata similar to GPS?" Locata website, available at www.locata.com/technology/locata-tech-explained/how-is-locata-like-gps/, accessed August 25, 2016.
[122] As of 2016, the system's ability to meet the integrity and continuity requirements to support safety-of-life applications has not been fully demonstrated.

areas requires installation of significant infrastructure, and likely precludes use over open ocean waters.

4.2.6. Cellular telephony LTE (Long-Term Evolution)

The LTE cellular telephone network infrastructure has some capability to derive geographic position through multilateration and other positioning techniques.[123] In fact, this positioning approach has some distinct advantages in certain environments, such as urban canyons where GPS satellite visibility is often impaired.[124] The advantages of this approach include a low cost of entry, since there is extensive existing infrastructure (i.e., cellular towers and antennas) and the positioning devices (LTE smartphones and other devices) are already in widespread use.

However, the cellular network is currently highly dependent upon GPS timing signals to synchronize system operations, so the use of LTE for positioning and navigation must also include the widespread deployment of an alternative timing source. The LTE approach is most likely suitable only for surface modes where there is existing cellular infrastructure, and is unsuitable for aviation or maritime applications. Geographic coverage may also be limited where there is a lack of infrastructure in remote, underdeveloped or undeveloped areas.

4.2.7. Inertial Measurement Units

An Inertial Measurement Unit (IMU) uses precision gyros and accelerometers to estimate the direction, velocity and acceleration of an aircraft, ship or vehicle, relative to its initial reference or starting point, directional orientation, and velocity. A modern Inertial Navigation System (INS) typically combines an IMU with a high-precision GPS receiver (i.e., GPS with augmentation), which is used to establish the reference or starting point and provide intermittent updates.

The IMU permits accurate positioning and navigation between GPS updates, or when the GPS signal is unavailable (e.g., when a submarine travels underwater, or a vehicle enters a tunnel). However, since the coasting performance of the IMU (i.e., time interval between GPS updates) erodes with time, the precision and accuracy of the IMU device itself plays a significant role in

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[123] "Positioning with LTE." Ericsson AB, Stockholm, September 2011, available at www.sharetechnote.com/docs/wp-lte-positioning.pdf, accessed August 8, 2016.
[124] Fabian Knutti, et al., "Positioning Using LTE Signals," presented at the European Navigation Conference, April 2015, available at http://espace-ftp.cborg.info/1504ENC/fullpaper/FP_ENC-017.pdf, accessed August 25, 2016.

overall positioning precision. For example, a typical system might have a loss of precision of 0.1 nautical miles after 10 minutes, increasing up to 1.0 nautical mile after 28 minutes.[125]

An INS certified for use in aviation can cost in excess of $100,000 while the most accurate systems (e.g., those used aboard submarines, where the coasting performance might extend for several days) cost in excess of $1.0 million. Smaller, micro-IMUs are under development that could be installed in portable devices such as smartphones, but they are not yet widely available on the commercial market. The precision of these devices would need to be validated to support safety of life applications.

4.2.8. VHF Omnidirectional Range and Distance Measuring Equipment

The VHF Omnidirectional Range (VOR) system (operating in the 108.000-117.975 MHz frequency band) and Distance Measuring Equipment (DME) (VOR/DME) (operating in the 960-1215 MHz frequency band) are radionavigation systems currently utilized in aviation. The VOR receiver determines relative direction between the VOR transmitter and the aircraft, while the DME receiver determines the distance between the DME transmitter and the aircraft. The FAA plans on maintaining a minimum network of VOR stations and augmenting DME systems, to function as alternate PNT systems for aviation.[126] However, VOR/DME systems do not provide the accuracy or precision of GPS-based systems, and do not support the improvements in NAS overall system operations and aviation safety envisioned as part of the FAA's NextGen initiative.

4.2.9. Radar, Laser-Based or Optical Systems

Several autonomous research vehicles have employed radar, LIDAR (Light Detection and Ranging) or other optical positioning techniques to detect vehicles, pedestrians, obstructions, hazards and surrounding infrastructure (see figure 4-1). Initial research has been conducted on the use of range-finding techniques to determine position relative to known natural geographic features or built infrastructure.

In order to function as a viable alternative positioning system, a Radar/LIDAR/Optical system would require a current, accurate, 3D base reference map, which it would use to compare against its observed (actual) surroundings to determine current position. This precludes its use outside of any surveyed areas, such as in the open ocean or in rural, unmapped areas.

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[125] Data based upon specification for a Northrop-Grumman LCR-100N Hybrid Inertial Navigator; data sheet available at www.northropgrumman.litef.com/fileadmin/downloads/datenblaetter/datenblatt_lcr-100n.pdf, accessed July 31, 2016.

[126] U.S. Departments of Defense, Homeland Security, and Transportation, "2014 Federal Radionavigation Plan," National Technical Information Service, Springfield, Virginia, section 5.4, available at www.navcen.uscg.gov/pdf/FederalRadionavigationPlan2014.pdf, accessed August 22, 2016.

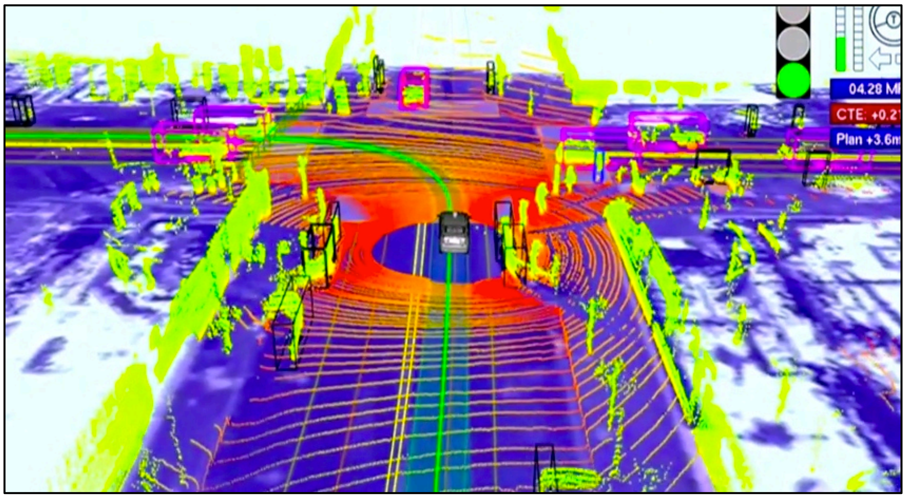

Figure 4-1: Example of Autonomous Vehicle LIDAR System View

Source: Google

4.2.10. Integrated Multi-Sensor Systems

Integrated multi-sensor systems combine individual techniques to establish a position. The operational concept is to utilize the strengths of each component system to augment or complement each other, while offsetting an individual component's weaknesses.[127]

[127] For example, see "Adaptable Navigation Systems," Defense Advanced Research Projects Agency website, available at www.darpa.mil/program/adaptable-navigation-systems, accessed August 22, 2016.

4.3. Alternative Timing Solutions

Table 4-2 lists timing solutions available as alternatives to GPS SPS timing signals.

Table 4-2: Alternative Systems Available for Timing

System or Application	Potential System Coverage				Timing Accuracy							Potential Suitability for Modal-Specific Applications						
	Space	Global	Regional	Local	>1 second	1s-1ms	1ms-1µs	1µs-100ns	100ns-50ns	50ns-10ns	<10ns	Aviation	Maritime	Highways	Local Roads	Railroads	Transit	Pipelines
Baseline: Global Positioning System (GPS) Standard Positioning Service (SPS)	Purple	Purple	Purple	Purple	Green	Green	Green	Green	Green	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Multi-Constellation Global Navigation Satellite System	Purple	Purple	Purple	Purple	Green	Green	Green	Green	Green	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
GPS Plus Augmentation (SBAS or GBAS)			Purple	Purple	Green	Green	Green	Green	Green	Yellow	Red	Green	Green	Green	Green	Green	Green	Green
eLoran (Enhanced Long Range Aid to Navigation)			Purple	Purple	Green	Green	Green	Green	Green	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Nationwide Differential GPS (NDGPS)			Purple	Purple	Green	Green	Green	Green	Green	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Locata®				Purple	Green	Green	Green	Green	Green	Yellow	Red	Red	Red	Yellow	Yellow	Yellow	Yellow	Red
Cellular telephony LTE (Long-Term Evolution)				Purple	Green	Green	Yellow	Red	Red	Red	Red	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow
Chip Scale Atomic Clock (CSAC)				Purple	Green	Green	Green	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Network Time Protocol (NTP)			Purple	Purple	Green	Green	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Precision Time Protocol (PTP)				Purple	Green	Green	Green	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
WWVB (radio station)			Purple	Purple	Green	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Oscillators				Purple	Green	Green	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Atomic Frequency Standard (AFS)				Purple	Green	Green	Green	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Fiber Optics				Purple	Green	Green	Green	Green	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red

Source: Volpe Center, using data from DOT Office of Position, Navigation and Timing

KEY TO TABLE 4-2

Potential System Coverage

Space — System can be used in space (above 100 kilometers)

Global — System appears capable of providing world-wide service

Regional — System appears capable of meeting modal applications at a regional level (i.e., large metropolitan area, an entire state, a river system, or a multi-state network)

Local — System appears capable of meeting modal applications at the local level (i.e., a city, port, airport, terminal, etc.)

Timing Accuracy

- System meets the stated performance standard.
- System usually meets the performance standard, but under certain circumstances, it might not.
- System does not meets the performance standard.

Suitability for Potential Modal-Specific Applications

- System appears capable of meeting all timing requirements for the specific modal application
- System appears capable of meeting many, but not all of the critical timing requirements for the specific modal application
- System is incapable of meeting the most critical timing requirements for the specific modal application

It should be noted that table 4-2 indicates the *potential* suitability of each alternative timing solution to meet requirements of specific applications within each mode. That determination was based upon suitability across the entire operating environment: vehicle, infrastructure and system. For example, a chip based atomic clock (CBAC) might be incorporated in the hardware of a centralized operating system for a networked transit vehicle tracking and dispatch system; however, a CBAC may not be a cost effective solution for deployment in individual transit vehicles. Consequently, the CBAC alternative would not meet the requirements across the operating environment of the entire mode.

4.3.1. Multi-Constellation Global Navigation Satellite System (GNSS)

This approach employs a multi-system GNSS receiver to determine time using two or more independent GNSS constellations, thereby reducing dependence on a single GNSS network and associated infrastructure. However, this approach may not adequately mitigate impact of radio frequency-based disturbances, particularly jamming, space weather, and spectrum encroachment.

4.3.2. GPS with Augmentation

As discussed in a previous section, GPS augmentation systems (whether ground-based or space-based) provide correction information that can mitigate the impact of some GPS disruptions. However, GPS with augmentation retains the underlying vulnerabilities of the GPS system (e.g., adjacent band interference, space weather, etc.).[128]

[128] For a discussion of deriving time from the GPS Wide Area Augmentation System in aviation, see S. Lo, D. Akos and J. Dennis, "Time Source Options for Alternative Positioning Navigation and Timing, August 2012," available at www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/documents/apnt/media/20120802timingwhitepaperapnt6-2012.pdf, accessed August 30, 2016.

4.3.3. eLoran

The eLoran system as contemplated will be able to achieve a timing accuracy of ±50 ns, which will meet nearly all of the time standards requirements across all transportation modes.

4.3.4. Nationwide Differential GPS (NDGPS)

As described in section 4.2.4, repurposing the existing NDGPS infrastructure could include an alternative timing solution, such as a ground-based constellation of GPS pseudolites that transmit of GPS-based timing signals, or to serve as eLoran sites.

4.3.5. Locata®

As described in section 4.2.5, Locata® is a proprietary positioning system that uses a ground-based array of transmitters and specially configured receivers to determine a position relative to a geographic reference point. While the system could be used to transmit timing signals, Locata® transmits in an unprotected, open-access frequency band (2.4 GHz), which would preclude use for safety or security applications. Further, the Locata® system requires a network of ground based antennas, which would require deployment of extensive infrastructure, which also limits its suitability for widespread use in aviation and marine environments.

4.3.6. Cellular telephony LTE (Long-Term Evolution)

The LTE cellular telephone network boasts significant global infrastructure, which make it an attractive, cost-effective option for alternative timing signals. However, since the system is currently dependent upon GPS timing signals to synchronize system operations, the LTE network must itself transition to its own alternative timing solution before it could be used as a viable GPS timing alternative. This approach is most likely suitable only for surface modes where there is existing cellular infrastructure, and is unsuitable for aviation or maritime applications that often operate well out of range of LTE infrastructure. Geographic coverage is also limited due to limited infrastructure deployment in remote, underdeveloped or undeveloped areas.

4.3.7. WWVB (radio station)

WWVB is a radio station located near Fort Collins, Colorado operated by the National Institute of Standards and Technology (NIST) that broadcasts time signals in two different formats at a frequency of 60 Hz.[129] WWVB time signals are used to synchronize a variety of consumer

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[129] For more information see NIST Special Publication 432, "NIST Time and Frequency Services, 2002 Edition," available at http://tf.nist.gov/timefreq/general/pdf/1383.pdf, accessed August 31, 2016.

electronics products (e.g., wall clocks, wristwatches, etc.). There are also network devices that can receive the WWVB signal, for use as a time reference.

There are a number of limitations that preclude the use of WWVB for many transportation applications. First, due to the nature of its signal propagation characteristics (i.e., transmitter location, transmitting power, frequency, atmospheric effects), WWVB time signals are only available in the continental U.S. (excluding Alaska and Hawaii), which precludes global use. Second, the accuracy of the WWVB signal (± 0.001 second) is insufficient to support most safety-of-life or operational applications.

4.3.8. Chip Scale Atomic Clock (CSAC)

These devices are sources of precise time, with an exceptionally low size, weight and power consumption (see figure 4-2). Measuring as small as 1.6 x 1.4 x 0.45 inches, CSACs represent a technological innovation that allows a stable, precise time source to be physically incorporated as part of the device hardware, rather than the device having to rely upon a separate, external timing source.[130] CBACs do not provide an absolute time value themselves; but, when integrated with a source of a precise timing signal such as GPS, a CBAC can maintain an accurate time during periods of GPS disruption.

Source: microsemi.com

Figure 4-2: Chip Scale Atomic Clock

Few manufacturers presently produce these devices, and the current cost (approximately $1,000) is likely to restrict use within transportation to larger system operators and service providers that require precise timing applications, with limited use by individual consumers and travelers.

4.3.9. Network Time Protocol (NTP)

NTP is a widely used Internet-based time protocol that synchronizes computer network clocks to a common reference time, Universal Time Coordinated (UTC).[131] NTP is designed to be fault-

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[130] See also, “NIST Chip-Scale Atomic Device Program,” presentation of the NIST Atomic Devices and Instrumentation Group, available at www.nist.gov/director/vcat/upload/VCAT-NIST-CSADemo.pdf, accessed August 31, 2016.

[131] For more information, see the Network Time Protocol website at www.ntp.org, accessed August 25, 2016.

tolerant, which automatically selects the best of multiple time sources to synchronize to. The time sources can include a variety of devices, including GPS time receivers, WWVB receivers, or atomic clocks. By definition, devices that rely upon NTP must be connected to wired or wireless network to function. NTP clients are also subjected to falsified time information, by malicious spoofing of the IP address of a valid NTP server; network authentication can reduce this risk.[132]

4.3.10. Precision Time Protocol (PTP)

PTP is network-based time protocol developed by the Institute of Electrical and Electronics Engineers (IEEE) that synchronizes computers to a common reference clock in a local area network.[133] Similar to NTP, PTP requires a precision time source, but the objective is primarily to synchronize time accurately across networked devices, rather than to an independent, standardized time such as UTC. This allows PTP to serve as a timing source across an entire enterprise system, but not necessarily between unrelated or unconnected systems.

4.3.11. Oscillators

Oscillators are precision electronic devices that use the mechanical vibration of a crystal (typically quartz) to create an electronic output signal – at a precise frequency – that can be used to measure time.[134] Oscillators alone cannot *establish* a precise time; rather, when integrated with a precise reference source of a timing signal such as GPS with augmentation, a high-performance oscillator can *maintain* an accurate time during periods of GPS disruption.[135] However, without a periodic update from a precise reference time signal, the accuracy of an oscillator's time signal will deteriorate over time, which may preclude its use in certain high-precision safety-of-life application.

Oscillators are capable of miniaturization, and are found in many portable devices such as "quartz" wristwatches. There are several design techniques that can increase the stability of a crystal oscillator over time, including temperature compensation, microcomputer compensation, voltage compensation, and oven control. These design techniques may increase the size, weight and power consumption of the oscillator, which could reduce the utility of this approach in small form-factor devices. In general, however, use of a high-precision oscillator is a cost effective means of maintaining a time signal during periods of GPS disruption.

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[132] "Best Practices for Improved Robustness of Time and Frequency Sources in Fixed Locations," p. 6.
[133] For more information, see "IEEE 1588™ Standard for A Precision Clock Synchronization Protocol for Networked Measurement and Control Systems," National Institute of Science and Technology website, available at www.nist.gov/el/isd/ieee/ieee1588.cfm, accessed August 31, 2016.
[134] Theron Jones, "Fundamentals of Crystal Oscillator Design," *Electronic Design* website, September 7, 2012, available at http://electronicdesign.com/analog/fundamentals-crystal-oscillator-design, accessed July 31, 2016.
[135] Sherman Lo, Dennis Akos and Joseph Dennis, op cit.

4.3.12. Atomic Frequency Standard (AFS)

An AFS is a high-precision time standard, typically determined by measuring the vibration of cesium atoms under highly controlled circumstances. The most accurate and precise AFS devices are "laboratory or primary standards" maintained by two U.S. government agencies, NIST and the U.S. Naval Observatory (USNO).[136] These time standards are used to synchronize time signals throughout the U.S., including the calculation of time, time interval and time corrections utilized by GPS satellites. When arrayed together with multiple precision time and frequency measuring components, these devices can achieve an accuracy that is equivalent to the gain or loss of one second in over more than 100 million years.[137]

Cesium-based atomic clocks are available on the commercial market. While these AFS devices do not achieve the exceptional accuracy of primary standards maintained by NIST or USNO, they are more than sufficient to meet any timing standards of the transportation sector. These devices require a reference time signal source (typically a GPS receiver). However, their size, power requirements, and cost limit their application to support for transportation infrastructure systems or networked operating systems.

4.3.13. Fiber Optic Timing Signal Transmission

Precision timing and frequency signals can be transmitted over optical fiber cables.[138] Using optical fibers as the transmission medium for the time signals, rather than RF transmissions through air or space, eliminates several sources of potential disruptions associated with GPS timing signals (e.g., adjacent band interference, jamming, or space weather). Since a physical connection (i.e., the fiber optic cable) is required between the source of the precision timing signal (e.g., an AFS; see 4.3.12, above) and the deployed system devices, this solution is viable only for land-based transportation infrastructure or large, complex transportation vehicles (e.g., ships), and is not available for smaller mobile applications.

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[136] "Cesium Atoms at Work," U.S. Naval Observatory website, available at http://tycho.usno.navy.mil/cesium.html, accessed July 30, 2016.

[137] "NIST-F1 Cesium Fountain Atomic Clock," National Institute of Standards website, available at www.nist.gov/pml/time-and-frequency-division/primary-standard-nist-f1, accessed August 15, 2016.

[138] L. E. Primas, G. F. Lutes and R. L. Sydnor, "Stabilized Fiber-Optic Frequency Distribution System," NASA Jet Propulsion Laboratory, TDA Progress Report 42-97, January-March 1989, available at http://ipnpr.jpl.nasa.gov/progress_report/42-97/97H.PDF, accessed August 29, 2016.

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