6. Science

Overview

Ultra-precise GNSS orbits and satellite clock corrections are the basis for all PNT applications in science and for society. Generation of these primary products require detailed knowledge of GNSS spacecraft properties (mass, surface properties, attitude) and absolute observations via Satellite Laser Ranging (SLR), requiring in turn laser retro-reflector arrays on-board GNSS satellites.

GPS is indispensable for Earth and atmosphere science. Global products include the International Terrestrial Reference Frame (ITRF) with cm-accuracy in position and mm/year-accuracy in velocity of its globally distributed sites, the monitoring of Earth rotation, in particular polar motion and length of day, global change monitoring, including the detailed sea level changes over decades.

GPS is one of currently four GNSS deployed or in deployment. Regional augmentations complement the GNSS. Research in multi-GNSS therefore has the potential to make all openly accessible GNSS services interoperable, in the sense that all systems can be used as one. SLR plays a key role to make multi-GNSS successful.

All global GNSS applications rely on a global network of permanent high-quality GNSS tracking receivers. The IGS, as shown in Fig. 6.1, consisting today of more than 400 sites, is the only global system for scientific use openly available (http://www.igs.org/). Scientific applications of GNSS are primarily based on IGS data and products such as, for example, maps showing total electron content in the ionosphere (Fig. 6.2). The IGS is based on a voluntary collaboration of more than 400 governmental and other organizations distributed all over the globe.

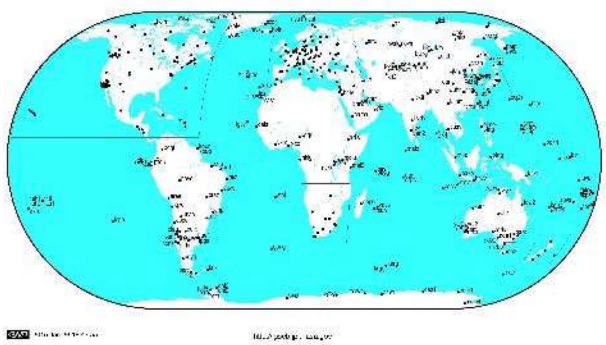


Fig. 6.1: IGS permanent tracking network

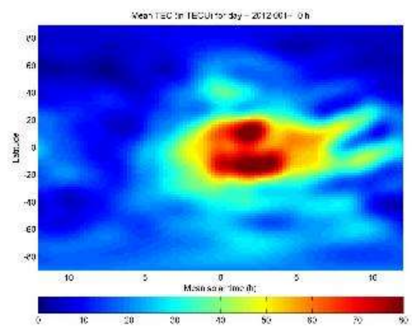


Fig. 6.2: Electron content on Jan. 1, 2012, 00^h-01^h

Utilization and Benefits

GNSS applications are not only important for science; they are relevant for the much larger international community of high-accuracy GNSS users. Virtually every first-order national survey is now based on GNSS.

GNSS applications include earthquake monitoring, tsunami warning, but also the determination of centimeter-level precise orbit of LEO satellites. Dedicated LEO missions like the German-led CHAMP (Challenging Mini-satellite Payload) mission, the U.S.-led GRACE (Gravity Recovery and Climate Experiment) mission, and the European Space Agency (ESA) -led GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) mission have determined the Earth's gravity field and its temporal variations with unprecedented accuracy in the first decade of the 21st century. Such missions provide one of the metrological foundations of global change monitoring. The GRACE-FO (GRACE Follow-On) mission is scheduled for launch early in 2018 to continue these crucial tasks in the next decade.

GNSS is of central importance for atmospheric research: the GNSS signals travel through the atmosphere, in particular the ionosphere with its free electrons and the lower atmosphere with its water vapor content. From ionospheric signal delays the number of free electrons between the satellite and the receiver can be extracted. Figure 6.2 (above) depicts the global distribution of the mean density of free electrons in the ionosphere as a function of the mean solar time and the geographical latitude during the first hour of the year 2012. The data was derived from all available GNSS signals travelling to all available receivers of the IGS network. GNSS is thus a unique tool for space weather monitoring.

The signal delays in the lowest parts of the atmosphere are used routinely to determine the water vapor content. Dedicated arrays of GNSS receivers are routinely used for weather prediction.

GNSS is routinely used for global time and frequency synchronization. The establishment of Universal Coordinated Time (UTC) cannot be imagined without GNSS.

Threats

High-accuracy GNSS products are of paramount importance for science and society. Such products are among other based on the open availability of GNSS-specific information from all GNSS providers, and on important assets like laser retro-reflectors on the satellites to enable SLR. The open availability of all GNSS-specific satellite information is currently not ensured and laser retro-reflectors are not available on all GNSS satellites.

Scientific GNSS receivers are so-to-speak the "Formula-I" GNSS user equipment, extracting "the last bit of information" out of the GNSS signals. Scientific GNSS receivers are, however, extremely vulnerable to interference, be it intentional or unintended.

Recommended Actions

In order to ensure high-accuracy multi-GNSS applications, the following action items are proposed from the point of view of science:

- Minimize bureaucratic obstacles hindering the use of other GNSS open services and endorse all measures to mitigate or to avoid interference
- All future GPS satellites should be equipped with laser retro-reflector arrays to enable independent orbit validation
- There needs to be easy access to GPS satellite characteristics required for precise orbit determination, and encouragement for other GNSS providers to provide the same to the science community
- Support all monitoring and coordinating activities for scientific GNSS applications of the IGS and ICG, in particular in the area of multi-GNSS use

Summary

GPS is one of two fully deployed GNSS and provides, with its 30+ active satellites, the backbone for all GNSS applications striving for highest accuracy, which include science applications. The IGS organizes the global tracking of all fully and partially deployed GNSS and coordinates the generation of highest accuracy products based on these data, including precise orbits for all active GNSS satellites, the coordinates and the motion of the globally distributed tracking sites (ITRF), precise length of day and polar motion, and atmosphere information related to space weather (ionosphere) and normal weather (troposphere). The maintenance of ITRF, the monitoring of the Earth's rotational characteristics, and the monitoring of the Earth's atmosphere are not possible without high-accuracy GNSS, in particular GPS.

7. Spectrum

Overview

GPS and other GNSS operate in spectrum allocated by the ITU to RNSS. Ensuring the continuity of the GPS/GNSS services requires protection of RNSS spectrum use from interference.

Utilization and Benefits

Protecting the availability and reliable reception of PNT information, delivered by GPS/GNSS satellite signals, benefits users in a broad range of applications. GPS technology innovation is an engine of the national and global economies. GPS/GNSS technology enables safer and more efficient transportation by land, sea, and air. GPS/GNSS applications improve productivity, efficiency, and sustainability in: agriculture and food security; disaster risk reduction; emergency response; surveying and mapping; construction; air, maritime, and land transportation; scientific research; mobile broadband communications; financial operations; power grids; and other critical infrastructure.

Threats

Access to radio frequencies free of harmful interference is crucial for reliable GPS/GNSS receiver performance. GPS/GNSS receivers operate below the ambient noise level in the RNSS spectrum when receiving PNT information delivered by signals from GPS/GNSS satellites operating over 12,550 miles from the Earth's surface. Emissions which raise the noise level in the GPS spectrum can harm the functioning of GPS receivers and constrain the development of new innovative applications.

Interference affecting the availability and reliable reception of GPS/GNSS can come from a variety of sources, including radio emissions in nearby bands, intentional or unintentional jamming, naturally occurring space weather phenomena, and potential incompatibility of new radio technologies.

Recommended Actions

Protecting the capabilities of GPS/GNSS receivers that operate below the ambient noise floor requires prudent spectrum management, including: sensible spectrum regulations (domestic and international) that minimize human-generated sources of interference affecting the availability and reliable reception of GPS/GNSS; interference detection and mitigation efforts; and law enforcement.

- Spectrum Regulations: The ITU publishes the International Radio Regulations, which is treaty-level text that contains the international rules on spectrum use. To minimize interference among different radio systems, the fundamental approach is to divide radio frequency spectrum into blocks known as allocations that group together similar radio services determined to be compatible. The Radio Regulations are the result of more than a century of detailed technical compatibility studies by engineers and other subject matter experts worldwide, and are constantly reviewed to consider new radio technologies. The RNSS frequency allocations were made following such technical compatibility studies. New radio technologies or expansions of existing technologies need to take the RNSS allocations, where all GNSS operate, into account. When setting national regulations, applying the ITU Radio Regulations and Recommendations to avoid introducing interference in the RNSS spectrum, gives the continuous reception of GPS/GNSS PNT information the best opportunity to work effectively and efficiently.

- Interference Detection and Mitigation: Ensuring that the Radio Regulations and related national regulations are followed requires monitoring the RNSS spectrum where GPS operates. To detect signals that can disrupt GPS signals requires special techniques such as geolocation and dense detector networks.

- Spectrum Enforcement: GPS/GNSS jammers are illegal and nearly all countries have national regulations that prohibit their manufacturer, import, sale and use. National market surveillance authorities need to ensure that illegal jammers are not available on the market and need to enforce strict measures as appropriate. When interfering emissions occur in RNSS allocations where GPS/GNSS operates, they should be found quickly, stopped, and prevented from reoccurring.

- International Spectrum Reporting: At the 2017 session of the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), the ICG proposed that under the Subcommittee's regular agenda item, "Recent Developments in Global Navigation Satellite Systems," a general exchange of information related to GNSS spectrum protection and interference detection and mitigation should be included. Beginning in 2018, Member States of the United Nations have begun to report on a voluntary basis on: (a) National RNSS Spectrum Allocations and Consistency with ITU Allocations; (b) Regulations Regarding Non-licensed Emissions Limits From Radio-frequency (RF) Emitters and Non-emitters; (c) Planned or Existing Laws and Regulations Related To The Manufacture, Sale, Export, Import, Purchase, Ownership, and Use of GNSS Jammers; and (d) Domestic Efforts To Detect and Mitigate GNSS Interference, with the overall goal of promoting effective use of GNSS open services by the global community. We recommend that:

- Support the proposal at the ICG regarding the international general exchange of information related to GNSS spectrum protection and interference detection and mitigation
- Coordinate with the NSpC on GPS/GNSS spectrum issues as it will participate in ITU's next WRC in November 2019

Summary

The ITU Radio Regulations are a sound basis for national regulations governing frequency use, especially for GPS/GNSS. For over two decades, the U.S. GPS PNT service has been globally pre-eminent, in large part due to committed spectrum leadership and effective national regulations that protect GPS utility while enabling new communications services where feasible. Prudent spectrum management enables continued realization of the benefits of GPS PNT innovation for the nation and society at large.

8. Transportation (Non-Aviation)

Overview

The use of GPS in surface transportation is estimated to exceed US$ 25 Billion annually. Every sector of surface transportation has become dependent on GPS.

Utilization and Benefits

Mapping and Guidance: Mapping such as Google and directions on internet, smart phones, and in-vehicle are used by businesses and individuals ubiquitously.

Portable navigation devices are affordable and widely available (image courtesy of Garmin Corporation).

Traffic Information: Traffic information is also widely available on the Internet, on smart phones, and on in-vehicle navigation units.

A free website provides real-time traffic information for Midwestern cities including Pittsburgh, Pennsylvania (image courtesy of localconditions.com).

Public Transit: Arrival times of buses and trains are widely available on internet, smart phones, and displays at stops. Public transit operators are using the GPS in their vehicles to improve vehicle dispatching, plan bus routes and vehicle maintenance, and send arrival times and traffic jam alerts to riders.

Bus shelters in Chicago provide arrival information based on GPS tracking of buses (photo courtesy of Ygomi LLC).

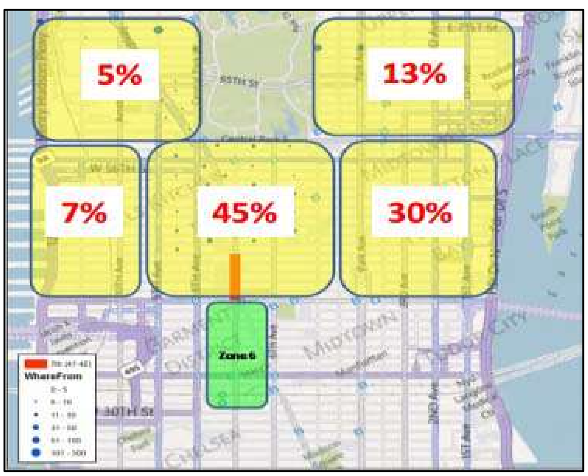
Vehicle Communications: In-vehicle telematics including automated emergency call are becoming widespread in new vehicles sold in the U.S. vehicle-to-vehicle (V2V) communications are planned to reduce vehicle accidents.

General Motors is one U.S. auto maker that is demonstrating V2V technology (photo courtesy of General Motors Corporation).

<u>Automated Driving</u>: Levels of automated driving in vehicles are being developed to reduce accidents and support people who have difficulty driving. These systems often include mapping and GPS.

A Chevrolet Bolt is equipped with sensors for development of automated driving (photo courtesy of General Motors Corporation).

<u>Traffic Management</u>: Traffic management authorities use GPS information to identify traffic patterns. Such data is used to plan road construction and maintenance, and set variable toll rates and speed limits.



For the Times Square Reconstruction Project in New York City, GPS-determined origin and destination zones (yellow) of taxi trips through the construction area (green) were used to identify likely detours while planning construction closures (image courtesy of New York City Department of Transportation).

<u>Logistics</u>: Freight handling companies are equipping vehicles and containers with GPS to improve efficiency and security. Uses include fleet management, load and delivery route optimization, real-time delivery assignments, and shipment tracking and monitoring.

Intermodal shipping containers on railway flat cars are tracked with GPS devices (photo by Tyler Silvest, licensed under the Creative Commons Attribution 2.0 Generic license).

<u>Inland Waterway Transportation</u>: The inland waterways of the United States include more than 25,000 miles of commercially navigable waters. River transportation is an important part of the integrated international multimodal transportation system. These waterways carry recreational craft as well as domestic and international cargo. GPS is the backbone of positioning, timing, navigation, tracking, and identification for the safety and security of river craft and infrastructure.

A single 15-barge tow, such as is common on the Upper Mississippi, is equivalent to about 225 railroad cars or 870 tractor-trailer trucks (photo by Ed Schipul, licensed under the Creative Commons Attribution-Share Alike 2.0 Generic license).

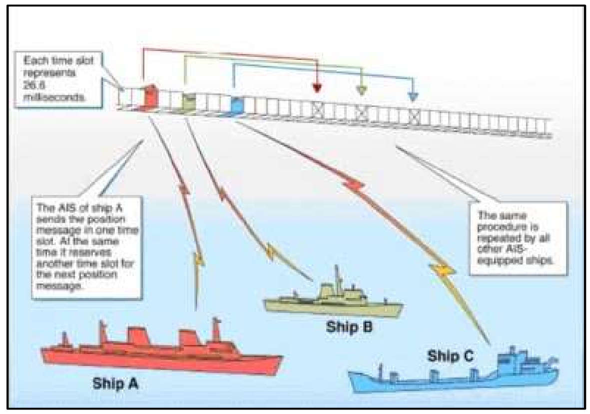
<u>Maritime Transportation</u>:

International maritime shipping is essential for global trade and for the global economy. Indeed, more than 80 percent of global trade relies on ship transportation. Maritime shipping provides a dependable and low-cost means of transporting goods globally, facilitating commerce, and helping to create prosperity for the nation.

Maritime shipping is the most energy-efficient, cost-efficient, and environmentally friendly means for the long-distance and high-volume transportation of goods, and is a key element for a sustainable global transportation system for U.S. business.

Safe and efficient navigation of ships depends on GPS during all phases of any voyage including oceanic passages, coastal approach, and entry into port. It is essential for route optimization, collision avoidance, emergency alert signals, search and rescue operations, and operating broadband ship communication systems. Ship management relies on GPS for purposes such as vessel monitoring, traffic management, fleet tracking, and management and national security purposes. GPS will play an enabling role in the development of future autonomous operations.

The TransAtlantic Lines ship MV TransAtlantic (photo courtesy of the United States Navy).



Position and timing information for an automatic identification system (AIS) is normally derived from an integral or external GPS receiver (graphic courtesy of the United States Coast Guard).

The U.S. is a signatory to the International Convention for the Safety of Life at Sea (SOLAS), which mandates a range of safety systems for ships, including those that depend on GPS for functionality such as AIS, voyage data recorders (VDRs), emergency positioning indicating radio beacons (EPIRBs), and the Global Maritime Distress Safety System (GMDSS).

GPS, increasingly accompanied by other GNSS systems, is in practice the sole source of PNT on board ships. GPS signal interference, whether intentional or unintentional, will thus greatly hinder maritime navigation and safety. GPS is essential infrastructure needed to maintain and further develop maritime shipping. GPS needs to be globally and continuously available, reliable, and accurate.

Threats

GPS and other GNSS are in practice the only source of PNT data for many land vehicles and ships. This presents a single point of failure.

Signal interference, intentional or unintentional, threatens all GNSS users. A conversion from satellite use to ground use of communications frequencies close to GPS would significantly degrade GPS in land vehicles. Spoofing and jamming are becoming true infrastructure threats, especially as connected and automated vehicles are rolled out.

Opportunities

Opportunities include emerging alternative backup capabilities for PNT and, also, more competent and robust receivers.

Recommended Actions

To protect the huge economic benefit of GPS/GNSS to surface transportation and other high precision applications, the PNTAB recommends the following:

- Keep spectrum for ground communication adequately distant from GPS spectrum
- Adopt approaches to harden GPS devices to recognize jamming and spoofing and counteract them
- Encourage GNSS manufacturers to offer more competent and robust receivers and antennas, and encourage product manufacturers to incorporate enhanced GNSS receivers in their products
- Encourage diversification of PNT sources. Have the FCC remove the requirement for licensing of non-Federal use of foreign GNSS
- Select and implement backup capabilities for GPS per NSPD-39

Summary

The use of GPS in surface transportation has become ubiquitous and of great economic benefit. It needs to be protected from the encroachment of more powerful signals in adjacent bands.

Acronyms & Definitions

AIS	Automatic Identification System (for ships)
ADS-B	Automatic dependent surveillance –is a surveillance technology in which an aircraft determines its position via satellite navigation and periodically broadcasts it, enabling it to be tracked.
ATC	Air Traffic Control
BeiDou	China's GNSS
CHAMP	Challenging Mini-satellite Payload space mission
COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
DHS	Department of Homeland Security
DoD	Department of Defense
E911	In the U.S. E911 (Enhanced 911) is support for wireless phone users who dial 911, the standard number for requesting help in an emergency. Since wireless users are often mobile, an enhancement was needed to 911 service that allows the location of the user to be known to the call receiver.
EGPWS	Enhanced Ground Proximity Warning System
eLoran	Enhanced Loran
EPIRB	Emergency Positioning Indicating Radio Beacons (for ships)
ESA	European Space Agency
EU	European Union
FAA	Federal Aviation Authority
FCC	Federal Communications Commission
FMS	Flight Management System
GA	General Aviation
Galileo	European Union's GNSS
GBAS	Ground-Based Augmentation Systems
GLONASS	Russia's GNSS
GMDSS	Global Maritime Distress Safety System
GNSS	Global Navigation Satellite System (i.e. GPS, GLONASS, Galileo, BeiDou, etc.)
GOCE	ESA's Gravity Field and Steady-State Ocean Circulation Explorer space mission
GRACE	Gravity Recovery and Climate Experiment space mission
GRACE-FO	GRACE Follow-On space mission
GPS	U.S. Global Positioning System
GPS IIF	GPS Block IIF (all 12 satellite vehicles have been launched)
GPS III	GPS Block III (1st launch currently expected in Dec.2018)
GPS-RO	GPS Radio Occultation
Kalman Filter	Algorithm that uses a series of measurements observed over time, containing statistical noise and other inaccuracies, and produces estimates of unknown variables
ICG	UN International Committee on GNSS (www.unoosa.org/oosa/en/ourwork/icg/icg.html)
IGMA	International GNSS Monitoring and Assessment
IGS	International GNSS Service (www.igs.org)
ISS	International Space Station
ITRF	International Terrestrial Reference Frame
ITU	International Telecommunication Union
km	kilometer

L1 C/A	GPS L1 Coarse/Acquisition Signal, also known as the GPS 1st civil signal
L1C	GPS 4th civil signal – new signal on GPS Block III vehicles intended to be interoperable with the Galileo Open Service (OS)
L2C	GPS 2nd civil signal – intended to primarily support surveyors and science applications
L5	GPS 3rd civil signal – intended for safety-of-life aviation applications
LEO	Low Earth Orbit
LORAN	Long-Range Navigation. Loran-C was a ground-based navigation system operated by the U.S. Coast Guard. In accordance with the 2010 DHS Appropriations Act, the U.S. Coast Guard terminated the transmission of all U.S. Loran-C signals on 8 Feb 2010. (https://www.gps.gov/policy/legislation/loran-c/)
M-Code	GPS Military Signal
MGUE	Military GPS User Equipment
microsecond	.000001 seconds
mm	millimeter
NCC	DHS National Cybersecurity & Communications Integration Center National Coordinating Center for Communications
NCO	National Coordination Office (see www.gps.gov)
NGA	National Geospatial-Intelligence Agency
NSpC	National Space Council
NSPD-39	National Security Presidential Directive 39, “U.S. Space-based PNT Policy,” Washington, D.C., December 8, 2004
OCX	GPS Modernized Ground Segment
PDD-21	Presidential Decision Directive 21
PNT	Positioning, Navigation, and Timing
PNTAB	National Space-based PNT Advisory Board
PTA	Protect, Toughen, Augment
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RNSS	Radio Navigation Satellite Services
RTCA	Radio Technical Commission for Aeronautics
SBAS	Space-Based Augmentation Systems
SLR	Satellite Laser Ranging
SOLAS	International Convention for the Safety of Life at Sea
SV	GPS Satellite Vehicle/s
TAWS	Terrain Awareness and Warning Systems
UAV	Unmanned Aerial Vehicle
UN	United Nations
UTC	Universal Coordinated Time
V2V	Vehicle to Vehicle
VDR	Voyage Data Recorder (for ships)
WAAS	Wide Area Augmentation System
WRC	World Radiocommunications Conference