

Programming Ubiquitous Things
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GPS Location

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Contents

- Introduction and some basic definitions
- GPS and Differential GPS
- Infrared and Ultrasonic Location Systems
- Location Estimation with 802.11
- Cellular-Based Systems
- Other Approaches
- Location-Based Applications and Services
- Conclusions

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Introduction



- Location is at the core of a number of **high-value applications** including:
  - emergency response, navigation, asset tracking, ground surveying, and many others
- The **market for GPS products and services** alone is more than **US$200 billion**
- **Location** is also commonly used to **infer other contexts**:
  - **symbolic location** is often a good **proxy for activity** (e.g., grocery store is indicative of shopping)
  - **social roles and interactions** can be learned from **patterns of colocation**, and
  - **physical activities and modes of transportation** can often **be inferred from the changes in location**

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Basic Definitions



- Location:
  - **symbolic** - symbolic location encompasses abstract ideas of where something is: kitchen, room 609, on a train arriving at Oslo central station, etc.
  - **physical** - physical location provides coordinates such as latitude and longitude
- Accuracy and Precision:
  - some inexpensive GPS receivers can locate positions to within 10 meters (grain size, accuracy) for approximately 95 percent (precision) of measurements
  - **grain size is accuracy**
  - **percentage is precision**
- To assess the **scale of a location system**, we consider:
  - its **coverage area per unit of infrastructure**, and
  - the **number of objects the system can locate per unit of infrastructure per time interval**
- Privacy:
  - location of a user is **obtained locally or on a central service**
- Infrastructure **cost**
- Per-client **cost**

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GPS

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GPS Basics (1/2)

- AVSTAR Global Positioning System (GPS) is by far **the most widely** used location technology
- It was estimated that by 2020, the number of **GPS chipsets** approaches **three billion**
- Dates:
  - the U.S. Department of Defense **approved the project in 1973**
  - the system was declared **fully operational in 1995**
- Cost:
  - **development** of GPS has been reported at **$14 billion**
  - its **annual operation** and maintenance cost is estimated at **$500 million**
- It is a **passive one-way** system where all signals are transmitted by earth-orbiting **satellites**, and **position determination happens at the receivers**
- It provides:
  - worldwide coverage
  - scales to an unlimited number of users,
  - preserves user privacy
  - supports a range of location services with accuracies that range from several meters to a few millimeters

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GPS Basics (2/2)

- Different types of GPS receivers vary in pricing:
  - from a **hundred dollars** for an inexpensive mass market model, to
  - tens of **thousands of dollars** for the more accurate solutions used for land surveying
- GPS was designed as a dual-use technology for both **military** and **civilian** use:
  - to maintain an accuracy advantage for the military, the original GPS design included a feature known as **Selective Availability**
  - it added **intentional noise** to the signals to degrade the accuracy of civilian GPS models
- Shortage of military-grade GPS receivers during the first Persian Gulf War in **1991**:
  - the U.S. Pentagon **disables Selective Availability** for the duration of the war,
  - and used **civilian receivers** to make up the shortfall
- Selective Availability was permanently **discontinued in May of 2000**:
  - in **December of 2004** the U.S. government reiterated its commitment to provide **GPS access free of direct user fees** for civil, commercial, and scientific uses
  - in **September 2007**, the U.S. Government announced its decision to **eliminate the feature** from future GPS satellites

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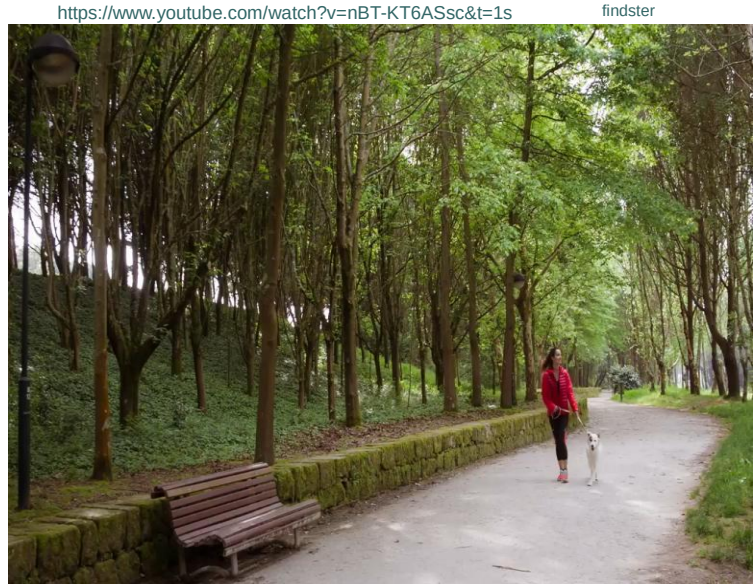
GPS Drawbacks

- Accurate GPS localization **requires an unobstructed view of at least four satellites**
- GPS signals do not penetrate well through walls, soil, and water:
  - thus, the system **cannot be used inside buildings**, **underground** (e.g., inside a mine or tunnel), or for **subsurface marine navigation**
- Signal can also be obstructed by large buildings in the so-called **urban canyons**
- Normally, location GPS based services require a **monthly extra-fee**

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Video Example (1/3) – how it works

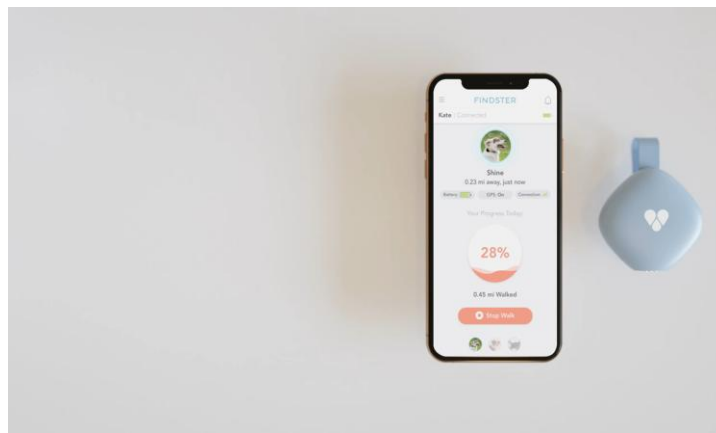
https://www.youtube.com/watch?v=nBT-KT6ASsc&t=1s findster



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Video Example (2/3) – GPS accuracy

https://www.youtube.com/watch?v=gIGxAC0rTiA&list=PLSFsgkVB0kB5Eedibl5GF4tClBEhkKVoj&index=4&ab_channel=Findster



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Video Example (3/3) – MAZE proprietary protocol

https://www.youtube.com/watch?v=59k-ZjKTtQY&list=PLSFsgkVB0kB5Eedibl5GF4tClBEhkKVoj&index=5&ab_channel=Findster

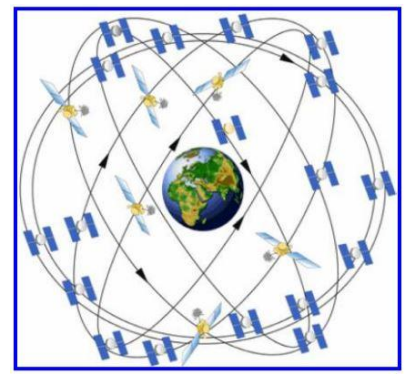


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Architecture (1/3)

- It consists of three distinct parts:
  - a constellation of Earth-orbiting **satellites** that broadcast a continuous ranging signal,
  - **ground stations** that update the satellites' coordinate projections and clocks, and
  - the **receivers** that use the GPS signals to estimate their position

- Earth-orbiting satellites:
  - **31 satellites** organized into **six circular orbits** 26,560 km above the Earth with a **12-h period**
  - full GPS coverage requires **24 GPS satellites**
  - the **additional satellites** operate as **active spares** to **accommodate occasional maintenance downtime** and to assure **system robustness**



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Architecture (2/3)

- Ground stations:
  - responsible for **monitoring satellite positions** and providing satellites with **clock corrections and satellite orbit updates**
  - there are enough ground monitoring stations to allow **each satellite to be simultaneously tracked by at least two monitoring stations**
  - simultaneous satellite tracking improves the precision of orbit calculations **increasing localization accuracy**



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Architecture (3/3)

- GPS receivers:
  - determine their position by **simultaneously tracking at least 4**, but commonly up to 12, satellites
  - can be **augmented with other sensors** (e.g., altimeters, accelerometers, and gyroscopes) to compensate for gaps in GPS coverage
- Receivers:
  - the original mobile units tested by the **U.S. Army in the 1970s weighed aprox. 12kg** and filled a backpack
  - today, typically around the **size of a cell phone**, and new single chip GPS implementations have made form factors as small as a wristwatch as possible







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Why GPS was Developed (1/5)

- Soviet Union launched the **first artificial satellite** (Sputnik 1) in 1957
- Two American physicists (William Guier and George Weiffenbach) at Johns Hopkins Univ. in the Applied Physics Lab. (APL) decided to **monitor its radio transmissions**:
  - they realized that, because of the Doppler Effect, they could **pinpoint where the satellite was along its orbit**
  - the Director of the APL gave them access to their UNIVAC to do the **heavy calculations** required
- Early the next year, Frank McClure, the deputy director of the APL, asked Guier and Weiffenbach to investigate the inverse problem:
  - **pinpointing the user's location, given the satellite's**
  - at the time, the Navy was developing the submarine-launched **Polaris missile**, which **required them to know the submarine's location**
  - this led them at APL to develop the **TRANSIT** system
  - in 1959, ARPA (renamed DARPA in 1972) also played a role in TRANSIT

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Why GPS was Developed (2/5)

- TRANSIT was first successfully tested in 1960:
  - it used a **constellation of five satellites**, and
  - could provide a **navigational fix approximately once per hour**
- In 1967, the U.S. Navy developed the **Timation** satellite:
  - it proved the feasibility of placing **accurate clocks in space**, a technology required for GPS
- In the 1970s, the ground-based **OMEGA** navigation system:
  - became the **first worldwide radio navigation system**
- Limitations of these systems drove the need for a more universal navigation solution with greater accuracy
- Although there were wide needs for accurate navigation in military and civilian sectors:
  - almost none of those was seen as justification for the **billions of dollars it would cost** in research, development, deployment, and operation of a constellation of navigation satellites
  - during the **Cold War arms race**, the nuclear threat to the existence of the United States was the need that did justify this cost in the view of the United States Congress
  - this deterrent effect is **why GPS was funded** and is also the reason for the **ultra-secrecy at that time**

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Why GPS was Developed (3/5)



- The nuclear triad:
  - consisted of the United States Navy's **submarine-launched ballistic missiles** (SLBMs), along with United States Air Force (USAF) **strategic bombers**, and **intercontinental ballistic missiles** (ICBMs)
  - considered vital to the nuclear deterrence posture, **accurate determination of the SLBM launch position** was a force multiplier
- Precise navigation:
  - would enable United States ballistic missile submarines to get an **accurate fix of their positions before they launched their SLBMs**
  - the USAF, with two thirds of the nuclear triad, also had r**equirements for a more accurate and reliable navigation system**
  - the U.S. Navy and U.S. Air Force were developing their own technologies in parallel to **solve what was essentially the same problem**
- To increase the survivability of ICBMs, there was a proposal to use mobile launch platforms (comparable to the Soviet SS-24 and SS-25):
  - the need to **fix the launch position** had similarity to the SLBM situation

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Why GPS was Developed (4/5)



- In 1960, the Air Force proposed a radio-navigation system called **MOSAIC** (MObile System for Accurate ICBM Control)
- A follow-on study, Project 57, was worked in 1963:
  - it was "**in this study that the GPS concept was born**“
- That same year, the concept was pursued as Project 621B, which had:
  - "many of the attributes that you now see in GPS“, and
  - promised increased accuracy for Air Force bombers as well as ICBMs
- Updates from the **Navy TRANSIT system were too slow for the high speeds of Air Force operation**

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Why GPS was Developed (5/5)

- The Naval Research Laboratory (NRL) continued making advances with their Timation (Time Navigation) satellites:
  - first launched in 1967,
  - second launched in 1969, with the
  - third in 1974 carrying the first atomic clock into orbit,
  - and the fourth launched in 1977

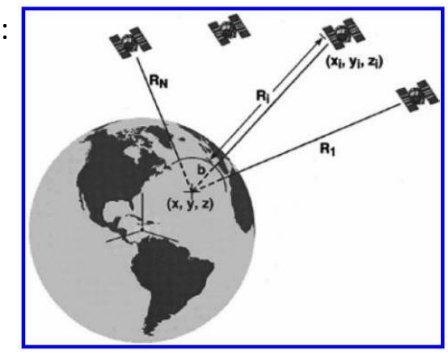
- Another important predecessor to GPS came from a different branch of the US military:
  - in 1964, the United States Army orbited its first **Sequential Collation of Range (SECOR) satellite** used for geodetic surveying
  - it included **three ground-based transmitters at known locations** that would send signals to the satellite transponder in orbit
  - a fourth ground-based station, at an undetermined position, could then use those signals to fix its location precisely
  - the last SECOR satellite was launched in 1969

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Algorithm (1/3)

- Supported by all GPS receivers and allows the receiver to:
  - **estimate its position in three dimensions** (latitude, longitude, altitude)
  - by **tracking four or more satellites**

- Location estimated:
  - computed from the **estimated positions of the satellites,** and
  - the **ranges from the receiver to those satellites**



- **Satellite locations are learned from the broadcasts from the satellites**:
  - **Ri is the distance between the receiver and satellite i**,
  - location is inferred by measuring the **transit time of the signal between the satellite and the receiver and multiplying by the speed of light**

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Algorithm (2/3)

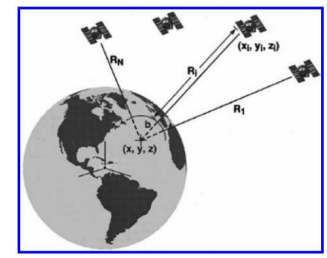
- Measuring the signal transit time accurately requires:
  - the satellite and receiver's **clocks to be tightly synchronized**
- In practice, the use of **low-cost crystal oscillators in the receiver** introduces:
  - a bias that makes the distance from the satellite appear **shorter or longer than the real value**
  - the receiver-induced bias will be the **same across all of the satellites**
  - **satellite** induced clock bias is less of an issue because of their **extremely accurate atomic clocks**
  - thus, the effect of the **receiver's clock bias can be removed** by treating it as an extra unknown in the location calculation

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Algorithm (3/3)

- The **receiver's location** in three-dimensional space (x, y, z) and receiver **clock bias b** is determined by solving the following equation for at least four satellites:

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b$$



- It requires at least **four satellites** (as opposed to the **three satellites that would be required with perfect clocks**)
- In cases where more than four satellites signals are available to the receiver:
  - the **redundant data** is used to try to **identify and eliminate error** in the location estimate
  - this is typically done using a least-squares estimation or with a Kalman filter

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Errors and Biases – Ranging Errors

- **Ionospheric delay** is the **dominant** source of **GPS ranging error**:
  - interaction of the GPS signal with ionized gases in the upper atmosphere,
  - **varies** with **time of day**, **time of year**, **solar flare activity**, and the **angle of entrance of signal** that affects the length of the path through the ionosphere
  - **models** of ionospheric delay have been developed, leaving a **residual delay with a 4-m mean**

- **Satellite coordinates errors**:
  - on the order of **2 m**
  - result of the **failure of the satellite position models** to account for all forces acting on the satellite
  - this can be **eliminated almost completely** by using precise orbit data (accurate within a few centimeters) that is made available over the Internet

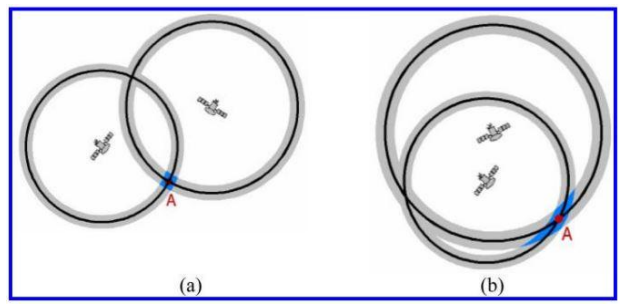
- Satellite's **atomic clocks are very stable**:
  - still can **accumulate up to 17 ns of error per day**, which translates to a **range error of 5 m**
  - to correct for this, the **satellite clock is continually monitored by the ground monitoring stations**, and **clock corrections are periodically transmitted**

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Errors and Biases – Satellite Geometry Errors

- The quality of the GPS location estimation depends on:
  - how well the tracked **satellites are spread across the sky**, and
  - in general, **satellite geometry improves as the distance between satellites increases**

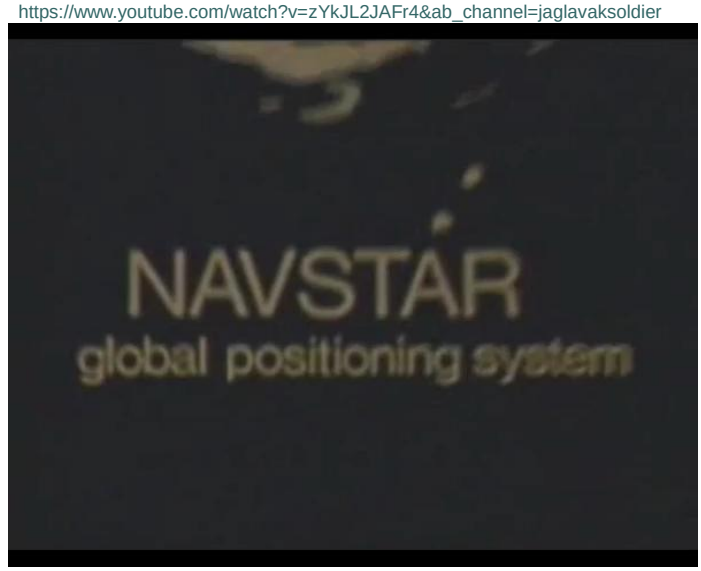
- The **size of the uncertainty area** where the receiver could be located **decreases**, as the **distance between the satellites increases** (see blue bands in the figure)



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Initial Video (Navstar was the initial name of GPS)

https://www.youtube.com/watch?v=zYkJL2JAFr4&ab_channel=jaglavaksoldier



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Differential GPS

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Main Idea of Differential GPS

- **Differential GPS takes advantage** of the fact that
  - satellite clock and satellite coordinate **errors**, as well as
  - ionospheric and tropospheric **delays**,
- exhibit **high temporal and spatial correlation** and are **very similar even hundreds of kilometers apart**

- Thus, differential techniques **take advantage of this** by:
  - coordinating **multiple GPS receivers that simultaneously track the same satellites**
  - by having **one or more GPS receivers fixed at known positions**, the observed **errors** from those receivers **can be transmitted to nearby roving GPS receivers**
  - these **roving units are then able to reduce their error** in proportion to their proximity to the site at which the correction was measured

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Real-Time Differential GPS

- Real-time differential GPS (**DGPS**) is a:
  - relative positioning technique that provides **sub-meter accuracy**

- A fixed receiver determines the DGPS corrections by
  - **comparing its measured satellite ranges** with ranges computed using its **known coordinates** and **the satellite coordinates** obtained from the **navigation message**

- The **DGPS corrections are then transmitted** over a ground- or satellite-based wireless link to the rover

- The **rover uses them to adjust** its ranging measurements

- DGPS is offered both as a local and a wide-area service



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Where such accuracy and precision
(sub-meter using the differential GPS)
would be really required?

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Real-Time Differential GPS – examples



- Maritime DGPS:
  - it consists of a **network of stations installed at lighthouses along coastal areas** in several countries around the world
  - each station operates by independently **broadcasting real-time DGPS corrections** (285- to 325-kHz frequency band)
  - these corrections are **available at no cost**, but **require a GPS receiver augmented** to receive the corrections
- Wide Area Augmentation System (WAAS):
  - it is a wide-area DGPS implementation that determines GPS range errors at **25 ground base stations**
  - these corrections are **broadcast from four geostationary satellites**
  - measurements from 27 U.S. airports show that WAAS provides **accuracy of 1.8 m at least 95%** of the time
- Others:
  - European Geostationary Navigation Overlay System (EGNOS)
  - Japan's Multifunctional Transport Satellite Augmentation System (MSAS)
  - India's GPS and GEO Augmented Navigation (GAGAN)

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Real-Time Kinematic



- GPS variant that achieves **centimeter accuracy**
- It uses an **alternative technique for satellite ranging**:
  - it is based on **measuring the number of fractional and full signal cycles** that happen between the satellite and the receiver
  - the range is then **computed by multiplying this value by the carrier's wavelength**
  - while the fraction of the last cycle is easy to determine, the **number of full cycles is ambiguous**
  - this ambiguity can be resolved by taking **simultaneous measurements at two receivers** (there are several techniques)
- After receiving the **base's coordinates and measurements** and **resolving the ambiguity**:
  - roving RTK receivers obtain **centimeter-level positioning accuracy**
- RTK is used in applications that require **extreme accuracy**:
  - surveying, aircraft landing, and maritime construction
- High-end RTK systems cost **tens of thousands of dollars** and **require line of sight between the coordinating GPS receivers**

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Enhancements and Other GPSs



- The next generation of GPS satellites are being deployed:
  - include **new PRN codes** that will enable civilian receivers to correct for the ionospheric effects that account for a large portion of the GPS error
- The **performance** of DGPS receivers is currently **limited by user equipment and multipath errors:**
  - as such, it is not expected to be affected by GPS modernization
- Other GPSs:
  - motivation is the reluctance to **base critical infrastructure on a service controlled by the armed forces of a foreign nation**

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Other GPSs

- **GLONASS** was originally deployed by the Soviet Union:
  - by 2010, GLONASS had achieved 100% coverage of Russia's territory and in October 2011, the full orbital constellation of 24 satellites was restored, enabling full global coverage

- The **Galileo** system is a 30-satellite location system under development by the European Union:
  - it will be under **full civilian control** under a public–private partnership
  - the EU owns the physical system as a public asset, and a concessionaire deals with day-to-day system operation
  - its architecture also allows for regional and local augmentation to improve service
  - it was expected to become **operational** sometime **between 2011 and 2013**
  - in July 2018, 26 of the planned 30 active satellites were in orbit
  - the complete 30-satellite Galileo system (24 operational and 6 active spares) was expected by 2021

- The planned improvements to GPS and GLONASS and the advent of Galileo:
  - over the next years, there will **be up to 80 satellites available for positioning**
  - this will lead to the introduction of **multisystem receivers** (dual GPS/GLONASS receivers are already available)

- It is estimated that:
  - **combining GPS, GLONASS, and Galileo**, a ground-based receiver should always be able to **see 21 satellites** except at extreme latitudes **compared to just 6 for the GPS-only solution**
  - a combined **GPS and Galileo system** should have a **median error of approximately 1.5 m**

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Comparison



Technology	Basic GPS	Differential GPS	Real-time Kinematic GPS
Accuracy	★★☆☆ 3D coordinates with 10 m median accuracy	★★★☆ 3D coordinates with 2 m median accuracy	★★★★ 3D coordinates with 10 cm accuracy
Coverage	★★★☆ Outdoors with clear view of 4+ GPS satellites	★★☆☆ Outdoors in USA — Requires clear view of 4+ GPS satellites and a WAAS satellite	★☆☆☆ Outdoors with 4+ GPS satellites and requires line-sight between mobile unit and surveyed unit
Infrastructure cost	★★★★ $14 B US initial cost + $500 M US yearly for global coverage	★★★★ WAAS satellites needed in addition to GPS constellation	★☆☆☆ Beyond GPS constellation, requires calibrated, surveyed ground unit
Per-client cost	★★★☆ GPS antenna and chipset required	★★★☆ GPS antenna and WAAS-capable chipset required	★☆☆☆ Special RTK unit required
Privacy	★★★★ Location is estimated passively on the GPS unit	★★★★ Location is estimated passively on the GPS unit	★★★★ Location is estimated passively on the GPS unit
Well-matched use cases	Outdoor navigation for land, sea and air, emergency response, turn-by-turn driving directions, outdoor mapping/information/tour guide services, personell/pet tracking, fitness/activity tracking, gaming	Outdoor navigation for land, sea and air, emergency response, turn-by-turn driving directions, outdoor mapping/information/tour guide services, personnel/pet tracking, fitness/activity tracking, gaming	Outdoor navigation requiring extreme accuracy, surveying, aircraft landing, maritime construction

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