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Navigation from Space

New Space Economy

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ETH zürich

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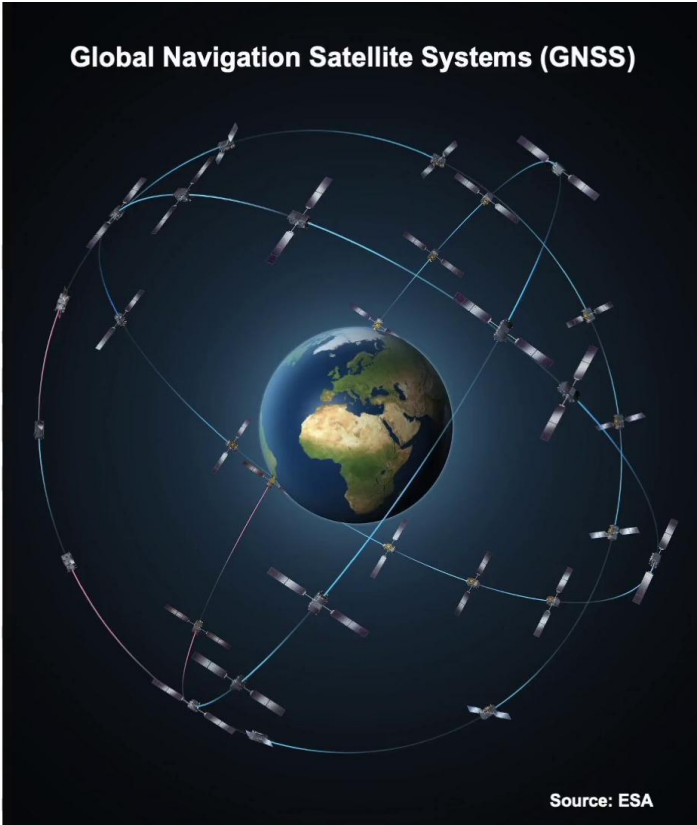


Video



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Introduction



Hello everyone and welcome to lecture about Navigation from Space. My name is Gregor Moeller and today I would like to give you an insight into Global Navigation Satellite Systems such as GPS, and I will explain why these systems are so useful for navigation.

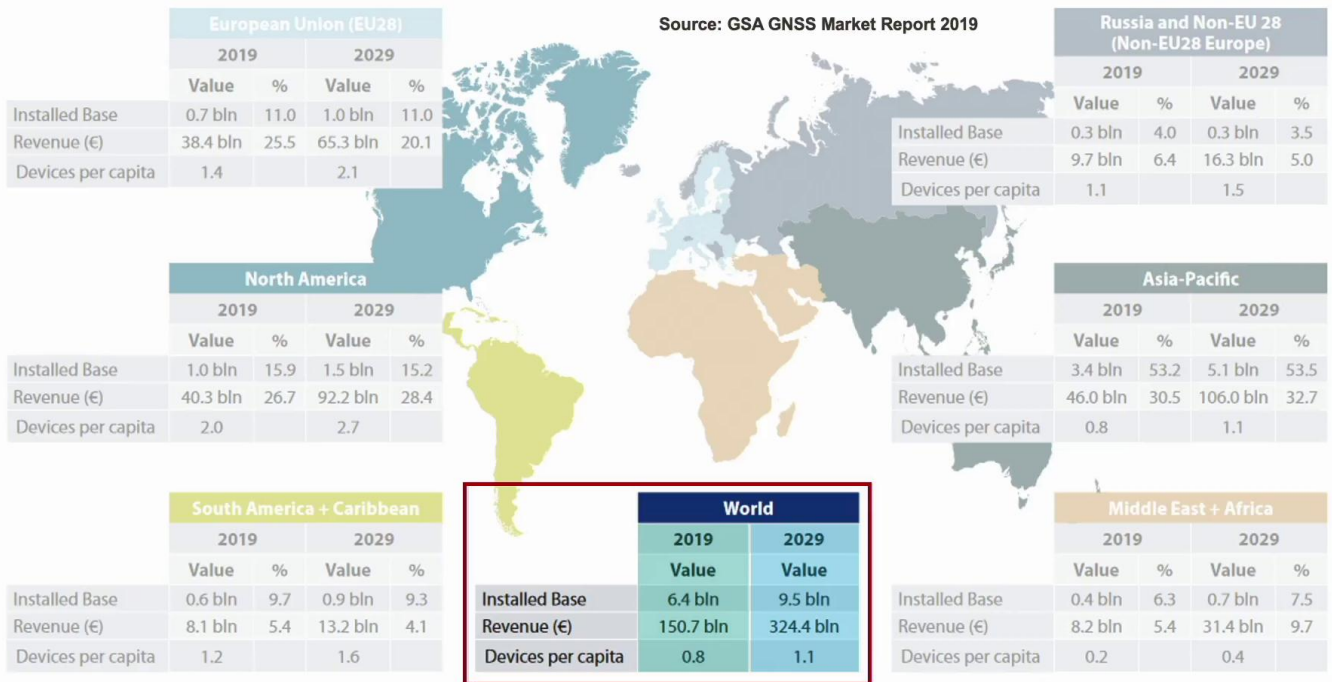
Notes

Summary



The global GNSS market

Source: GSA GNSS Market Report 2019



Over the last 30 years, the number of GNSS devices has continuously grown. From the first Navi in 1989 to about 6.4 billion GNSS devices in 2019. Based on current predictions, this number will further increase to about 9.5 billion GNSS device in the next 10 years. This means on average, each capita will have at least one GNSS device. So we can immediately see that the satellite navigation is still a growing market. Which is of interest not only from an economical point of view also enables a series of applications.

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Summary



Why GNSS?



- 3D position, velocity and time
- Everywhere on Earth and at any time
- Weather-independent
- Unlimited number of users
- Centimeter accuracy

To understand why GNSS is so attractive, we have to look more carefully into the specifications. First, Global Navigation Satellite Systems allow us to compute our 3D position and velocity but also accurate time information on the microsecond to nanosecond level. In addition, GNSS is available everywhere on Earth. And even above the Earth, as long as GNSS signal reception can be guaranteed. Furthermore, GNSS has been designed in such a way that it works under all weather conditions and allows for an unlimited number of uses. Well, I assume that most of you are familiar with the use of GNSS but maybe do not know so much about the technical realisation. Thus, in the following, I would go more into detail how this performance can be achieved. Now, I will demonstrate that with the right equipment and processing not only metre but centimetre position accuracy is possible.

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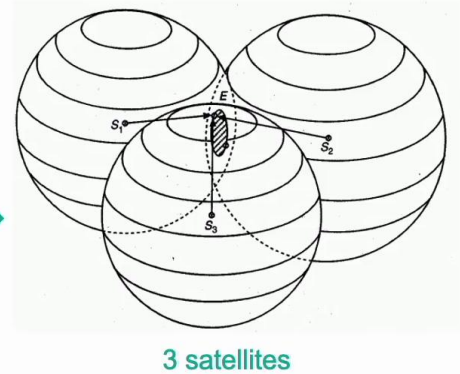
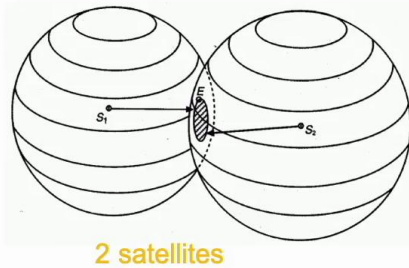
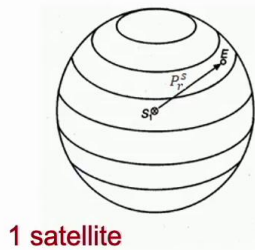
1m 05s

3D position, velocity and time

Basic principle of position determination with GNSS

Distance = Speed of light x **Signal travel time**: $P_r^S = c(T_E - T^S)$

Measurement



- In addition, a **fourth** satellite is needed for computing the **receiver clock offset**, i.e. to synchronize the the receiver clock with the satellite clocks.

From the basic concept, GNSS is a time-measurement system. When we know the travel time of the GNSS signal from the satellite to the receiver, we can multiply it with the speed of light and obtain the distance of the user to the satellite. This sounds trivial, but from one measurement alone we cannot compute the 3D position but only the sphere around the satellite on which the user must be located. This is illustrated on the left side for one satellite. In consequence, multiple satellites have to be observed at the same time and only a combination of three measurements gives us the chance to determine the user position. Conditions, therefore is that the satellite and receiver clocks are synchronised, but usually this is not the case. In consequence, the measured signal travel time is slightly incorrect. This is the reason why we call the measured distance in GNSS positioning to the distance up to the range. To compute the correct distance, an additional observation to a full satellite is necessary. This allows us to compute and to correct for the receiver clock error and to obtain our position. The general method is known as position fixing based on psuedoranges.

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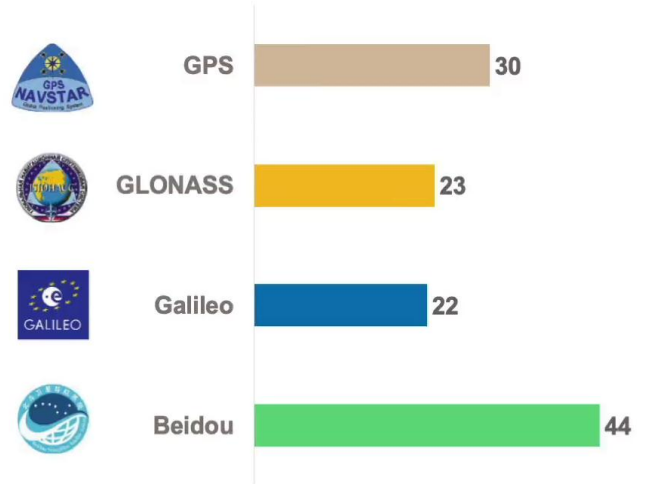


2m 14s

Everywhere on Earth and at any time



Operational satellites of the four Global Navigation Satellite Systems (as of August 24, 2021)



I'm sure most of you have already heard about GPS and maybe also about the other three Global Navigation Satellite Systems, namely GLONASS, Galileo, and Beidu. In fact, all four systems are based on the same measurement principle. To guarantee global coverage, each system is realised by a constellation of 22 up to 44 satellites as of August 2021. The satellites are well distributed over several orbital planes at a distance of about 20,000 kilometres. To give you an impression how a nominal GPS constellation looks like, let's have a look on the following animation.

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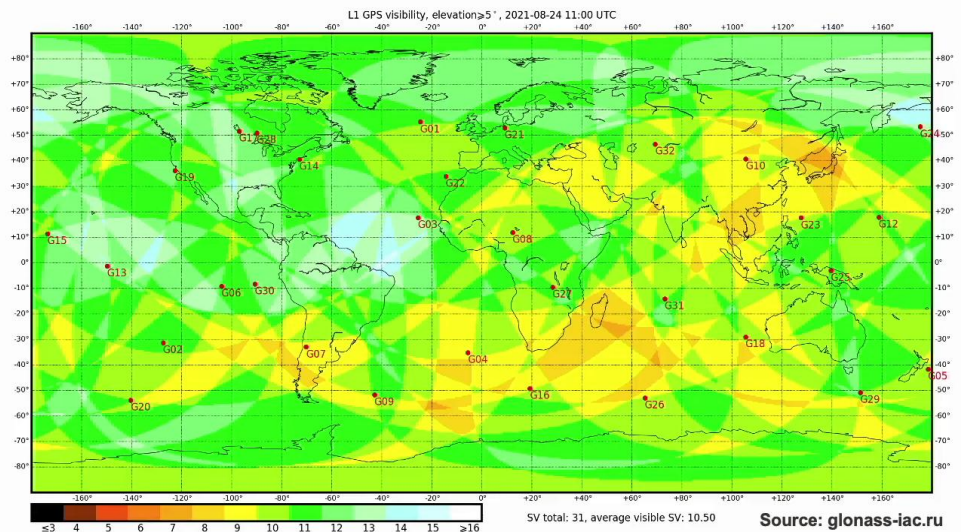
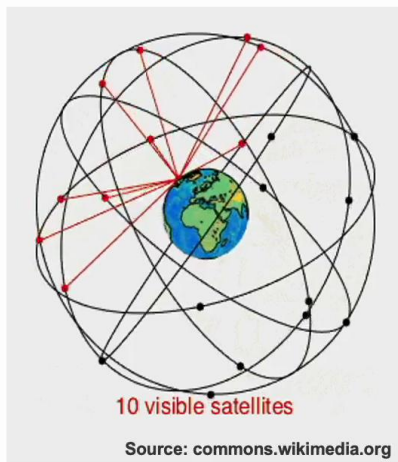
Summary



3m 40s

Everywhere on Earth and at any time

Visibility of GNSS satellites – exemplary for the GPS constellation



In this animation, on the left side, you see how the GPS satellites are distributed over six orbital planes. In addition, for a user in North America, the number of visible satellites is shown. Due to the movement of the satellites around the Earth with a velocity of about 14,000 kilometres per hour and the movement of the user, the number of visible satellites changes continuously. Now, if we do this visibility study for any point on Earth, we obtain a visibility map as shown here on the right side. Exemplary for one epoch in August 2021. This map shows the number of visible satellites which can be observed in the best case at this particular epoch. It varies between six and 16 satellites dependent on where you are. In a challenging environment, like in the mountains or urban canyons the situation can be completely different. In these situations, the number of visible satellites can be significantly lower. In case you navigate only with one system such as GPS, you might end up in situations in which a position determination is not possible anymore. Switching to more GNSS receivers increases the number of visible satellites and therefore, reduces the risk for GNSS outages.

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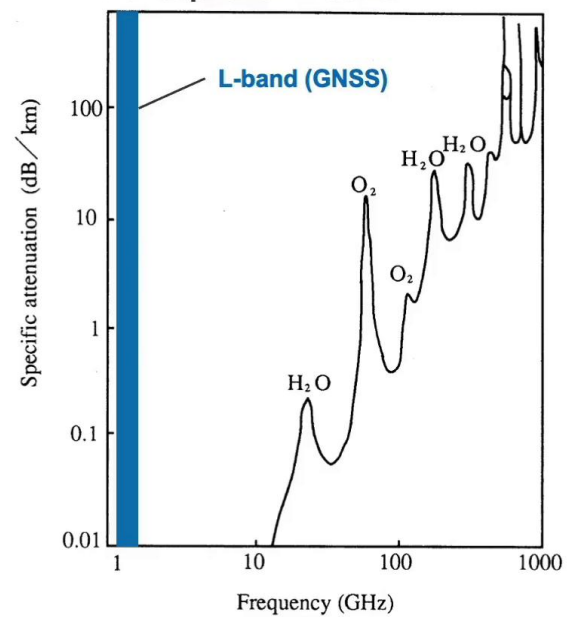
Summary



Weather-independent



Atmospheric windows



Another benefit of GNSS is its capability to operate under all weather conditions. This might sound trivial but requires careful selection of the signal bands. For GNSS, the so-called L-band is utilised. It is defined in the frequency range between one and two GHz. In this spectrum, the specific attenuation is low. It means the signal strength is not much affected by atmospheric water or other consideration. Furthermore, L-band seems to be very efficient in terms of performance and atteno-size especially for small form factors. In the following, I would like to show you how the individual frequencies within the L-band are distributed over the four Global Satellite Navigation Systems.

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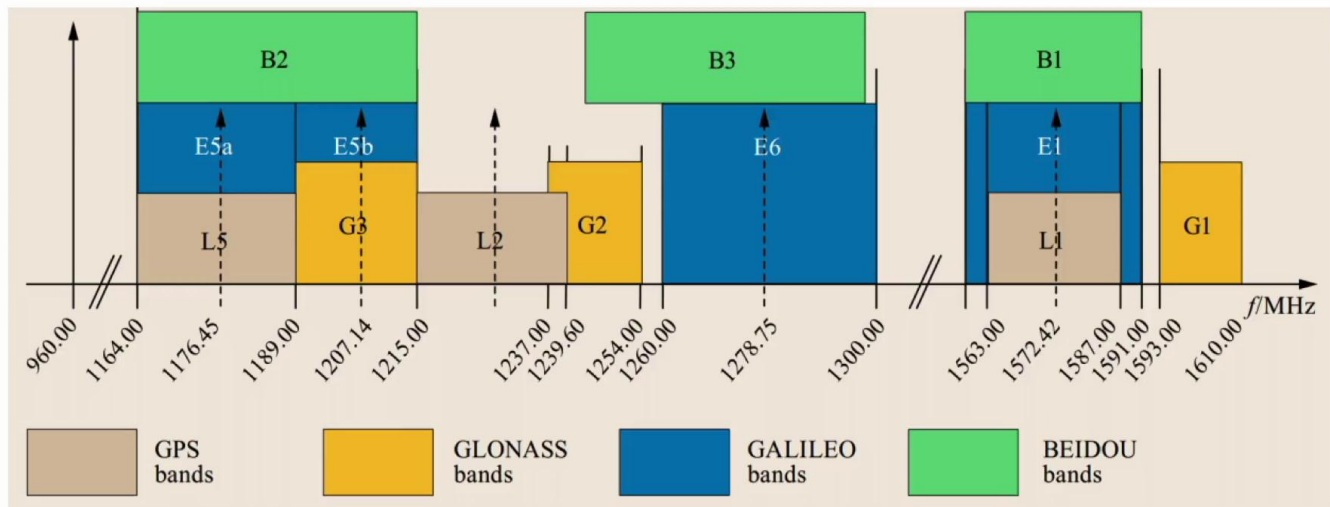
Summary



5m 54s

Weather-independent

GNSS frequency bands



Source: Teunissen and Montenbruck (2017)

The main message here is that each system operates on its specific frequency bands. With a few overlaps between the individual systems. As GNSS user you have to be aware that the current GNSS receivers on the market usually do not support all frequencies especially in the lower price range. In consequence, we have to be clear about your intended performance. In case five to ten metres accuracy is sufficient for your application, a single frequency GNSS receiver might be the best choice. For example, using the L1 or L5 frequency band. For higher accuracy, you should select a receiver which allows signal tracking on two frequencies. There are various combinations possible. For example, Galileo E1 and E5a, E5b or E6. In the best case, your receiver supports all four global satellite systems. In addition, you should be aware that not all satellites transmit all frequency bands. The same is also true for the services provided. For example, for the new Galileo High Accuracy Service, your GNSS receiver must be capable of tracking on E6. So dependent on your application, you have to decide on the right combination of frequency bands which shall be supported by your GNSS device.

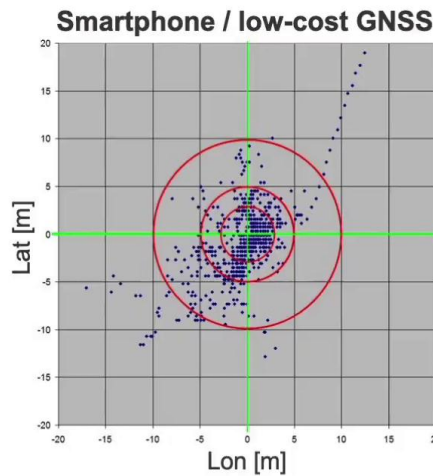
Notes

Summary



6m 47s

Centimeter position accuracy



Accuracy

3 m → 50 %

5 m → 76 %

10 m → 95 %



In the last part of the lecture, we will have a closer look into the main error services in GNSS. First, let's check the position accuracy possible with a single frequency GNSS receiver, its commonly used in smartphones. For recording of the GNSS data, I used an app called SensorLock. What we see here in this plot are the differences of the GNSS positions with respect to the reference position in latitude and longitude. From the scatter of the differences, the 2D position accuracy can be computed. In my test, I received a position accuracy of about three metres in 50% of the cases and ten metres in 95% of the cases. Which reflects more or less the expectations on such a device. To further increase the accuracy now let's see what we can do.

Notes

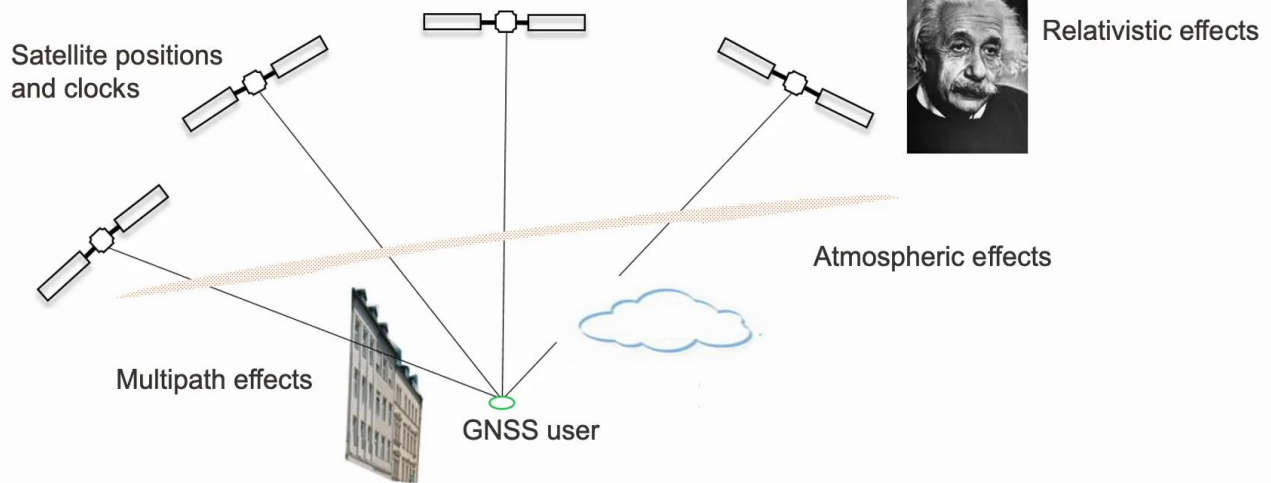
Summary



8m 19s

Centimeter position accuracy

GNSS error sources



- For **meter position accuracy**, the signal travel time has to be known by **3 nanoseconds** (0.000000003 sec)

The position accuracy is a consequence of all error sources affecting the GNSS servers. The main error sources can be divided into satellite dependent effects, relativistic effects, and so-called propagation effects including atmospheric delay and multipath. For centimetre position accuracy, all these errors have to be compensated, which is not a trivial task. For example, the atmosphere alone causes a signal delay of about three metres up to 100 metres. Since the atmosphere above 80 kilometre altitude is dispersive, meaning the delay is frequency dependent, we can use dual-frequency observations to compensate for almost 100% of the higher atmospheric effect, also known as ionospheric effect. For the remaining signal delay in the lower atmosphere, we can either use atmospheric models or estimate the atmospheric delay together with the user position. However, this requires usually longer installation time until the solution converges.

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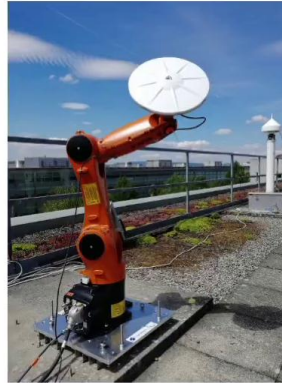


9m 19s

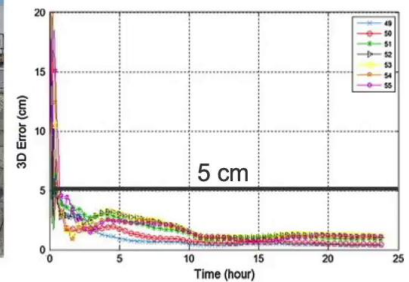
Centimeter position accuracy



High-precision GNSS



Source: Willi D. (2019)



How such a precise solution looks like is shown here in this example. With the proper equipment and processing strategy, centimetre precision accuracy can be easily obtained with GNSS. However, further significant research is necessary to make this level of accuracy available to mass-market applications.

Notes

Summary



10m 32s

What next?



- Advances in satellite technology
- Dual-frequency GNSS for smartphones (reduction of atmospheric effects)
- Galileo High Accuracy Service (dm-accuracy)
- Advances in signal processing (crowd-sourced, machine learning algorithms)

Since the beginning of satellite navigation, technological advancements are applied on the user's side but also to the satellites themselves. In fact, the entire constellation is continuously renewed. All satellites are replaced by new ones with new technology, new signals, and new services for both civilian and military uses. In the next few years, we can expect that smartphones will be equipped by default with dual-frequency, multi-GNSS receivers. The first mobile phones of this kind are available since 2019. They allow for positioning with metre or even submeter level accuracy. In addition, the Galileo users will benefit from a new service called Galileo High Accuracy Service, for two decimetre level accuracy. The necessary corrections for this service will be broadcasted on the E6 signal. The initial service will start most likely in 2022, allowing free-of-charge high accuracy positioning globally for everyone. In parallel, artificial intelligence and machine learning algorithms are used to further improve the GNSS data-processing to provide even greater performances not only for terrestrial navigation but also for drone or even spacecraft navigation.

Notes

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10m 55s

Conclusion



- **GNSS: primary choice for most navigation applications**
 - High accuracy
 - Almost 100% availability
 - Redundancy (multi-GNSS)
 - Small, low-cost and low-power

In fact, GNSS works also very well for satellites in low-Earth orbit. So we expect that in the next near future, GNSS will remain the primary choice for most navigation applications. With almost 100% availability and high redundancy guaranteed by multiple independent GNSS constellations. Dependent on your demands, you will find various GNSS devices on the market, ranging from low- grade, like in your smartphone to medium-grade receivers for centimetre position accuracy or even high-grade receivers for high-position applications. So dependent on your needs, you just have to select the right equipment.

Notes

Summary



12m 34s