Global Navigation Satellite Systems: Status, Plans and Threats

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Introduction

In this contribution the current status and future development of four Global Navigation Satellite Systems (GNSS) are reviewed. They are the American Global Positioning System (GPS), the Russian Glonass, the European Galileo and the Chinese BeiDou Compass.

All four systems offer, or will offer, civil navigation services (publicly open), as well as restricted access navigation services, which means for GPS, Glonass and likely for Compass as well, military services. The European Galileo system will offer so-called Publicly Regulated Services (PRS) for use by the government.

The basic principle of satellite navigation — referred to as standalone positioning, or single point positioning — consists of measuring, with a receiver on, or close to the Earth, distances from three satellites to the receiver, each time by observing the travel-time of the radio signal, as transmitted by the satellite. Three distances, to objects or points with known position coordinates — the satellites — allow us to determine the position of the user receiver, geometrically, in three dimensions. To this end, the GPS ground segment, with stations around the Earth, of which the position coordinates have been accurately established, and using the radio signals transmitted by the satellites as well, determines the positions of the satellites, predicts them ahead, and uploads the information to the satellites, so that they can relay this information to users all around the world.

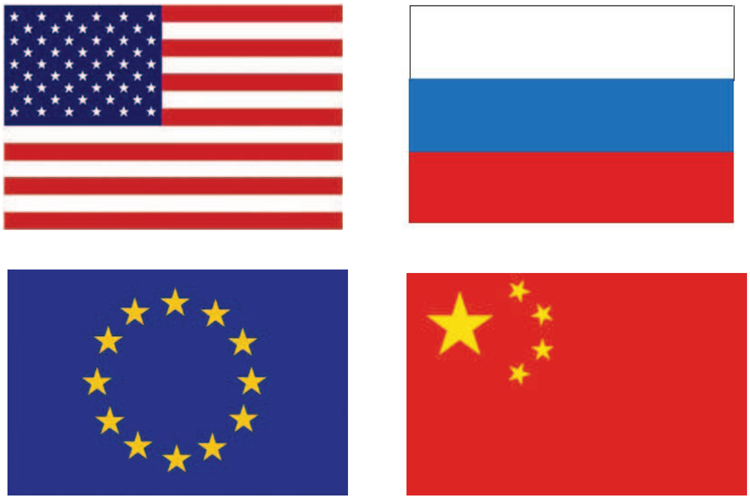


Figure 1: Nations currently operating and/or building a Global Navigation Satellite System (GNSS). The Global Positioning System (GPS) by the United States, Glonass by the Russian Federation, Galileo by Europe and BeiDou Compass by the PR of China.

One complication remains. The user receiver typically is not equipped with an accurate clock, like an atomic standard (which the satellites do have on board). When the user receiver clock is ahead, the measured distances are systematically too long, but all by the same amount. This problem is overcome by observing — simultaneously — at least a fourth satellite. With four distances, to satellites at known positions, the user receiver can determine its three-dimensional position, and its clock offset with respect to GPS system time as well. The resulting position accuracy lies in the order of 5–10 meter, under favourable circumstances, which is an open sky, and no tall obstables, like buildings, blocking the view.

In this contribution it is outlined that in the present decade, global satellite navigation will mature, with diversity of system control, and a rich variety of signals, though by means of a small case study — demonstrating how, in an unlikely event, navigation service can go wrong — a warning is issued against over-reliance on available satellite navigation services.

Global Positioning System (GPS)

The Global Positioning System (GPS) has been developed by the US Department of Defense (DoD), and is operated by the US Air Force (USAF). The first satellite was launched in February 1978. Various generations of GPS satellites are Block I, II, IIA, IIR and currently IIR-M. From this year on, launches of block IIF satellites are scheduled, and third generation GPS block III satellites are scheduled from 2014 onwards. Last year, the US Government Accountability Office (GAO) issued a report on GPS, doubting whether the Air Force will be able to acquire new satellites in time to maintain GPS service without interruption. According to analyses by the GAO, the constellation may fall below the nominal number of 24 satellites, in the years to come.

Figure 2: GPS block IIF satellite, to be launched from 2010 on. This series of satellites offers triple frequency civil signals.

The ground-segment of GPS orignally consisted of five stations (worldwide), and one at Cape Canaveral. In the meantime six ground-stations have been added. GPS is fully operational, currently with 31 satellites in orbit, instead of the nominal 24 constellation. The US Coast Guard is the primary point of contact for civilian users: www.navcen.uscg.gov.

Figure 3 (on top) shows the actual mission duration per satellite. The satellites are ordered, along the horizontal axis after launch date. The 7th and the 40th satellite were never put into orbit because of launch-failures. Satellites in green are still active today, as of February 2010, and some of them have been launched very recently, in March and August of 2009. The design lifetime of block II/IIA satellites is seven and a half years, and of block IIR satellites 10 years, with mean mission durations of six years and seven and a half years respectively. Only the first 11 satellites were block I satellites, the rest are all block II. It can be seen that in general GPS satellites largely outlive their mean mission duration and design life time. There are some 10 satellites exceeding even more than 15 years, which is double the mean mission duration!

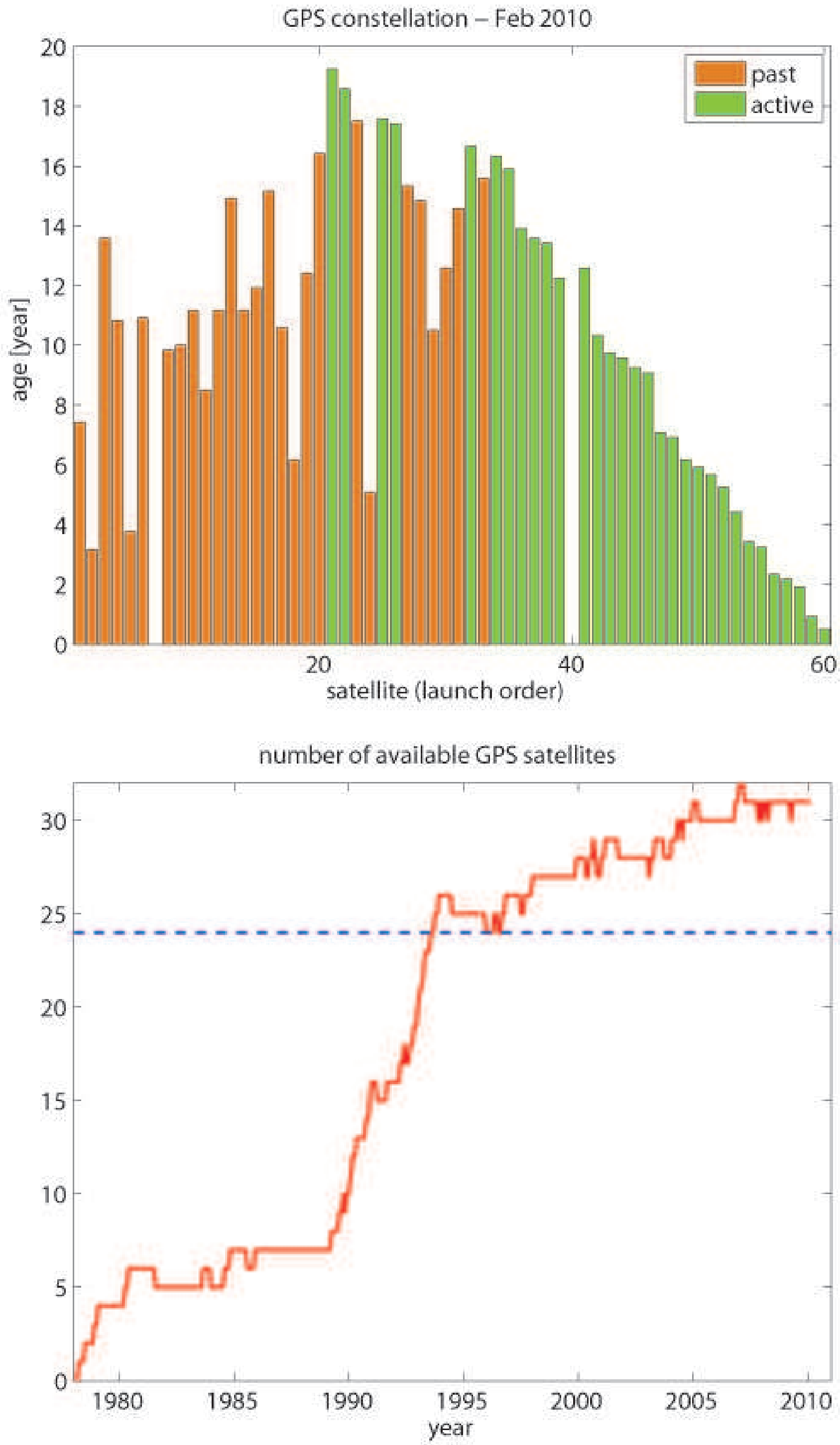


Figure 3: Top: active mission duration per satellite, green satellites are still active today. Bottom: the number of active GPS satellites as a function of time.

The graph at the bottom of Figure 3 shows the number of active GPS satellites in orbit as a function of time, ever since February 1978, up until today. The nominal GPS constellation consists of 24 satellites. Today there are 31 satellites, of which one is set unhealthy (PRN01/SVN49). So far, in a constellation with more than 24 satellites, typically newer satellites fly in tandem, side by side, with older satellites, by which we have, from the geometric point of view, effectively a 24 satellite constellation. Very recently (January 2010), the US Air Force has begun repositioning GPS satellites, as a transition to what they call a 24+3 constellation. This policy change was driven at least in part by the desire to improve satellite visibility for US and allied military operations in Afghanistan and Iraq, where mountainous terrain can hamper signal coverage for troops on the ground. The transition will take up to 24 months to implement fully.

Glonass

The GLObal NAvigation Satellite System (Glonass) has been built on the order of the Russian Ministry of Defence, and is maintained by the GUKOS. The first satellite was launched in October 1982. Since Autumn 2003, second generation satellites (Glonass-M) are being launched. A set of three Glonass-M satellites was launched, in one go, in December 2009. Third generation satellites (Glonass-K) are expected from this year onwards. They will offer civil signals on three frequencies.

The ground-segment of Glonass consists of four stations in Russia. Glonass has had a difficult time in the recent past, with only a few satellites in orbit. The system now seems to be approaching full operational capability. There are 20 satellites in orbit, of which two are in maintenance, as of February 2010. The point of contact for Glonass is the Russian Space Agency: www.glonass-ianc.rsa.ru.

Galileo

The Galileo system is being developed by the European Commission (EC) and the European Space Agency (ESA). Two prototype satellites have been launched so far, GIOVE-A in December 2005 and GIOVE-B in April 2008. The next step is to launch four satellites (later this year, and in 2011) for the In-Orbit Validation (IOV). A contract for 14 operational satellites was awarded in January 2010. These satellites should fly by 2014. The award of a subsequent 18 further satellites was left open. With the full constellation

Galileo should have 30 satellites in orbit (27, plus 3 active spares), but the final Full Operational Capability (FOC) date has not been specified yet.

The ground-segment of Galileo will consist of a worldwide network with about 40 stations. Useful websites on Galileo are www.gsa.europa.eu of the European GNSS Supervisory Authority, www.ec.europa.eu/transport/galileo of the European Commission, and www.esa.int/esaNA/galileo.html of ESA.

BeiDou Compass

The BeiDou (Compass) Navigation Satellite System is being developed by the Chinese government. The first Medium Earth Orbiting (MEO) satellites were launched in April 2007. The system has so-far three satellites in orbit (the third one, a geo-stationary satellite was launched in January 2010). The system will consist of 27 satellites, supplemented by five geo-stationary satellites, and three inclined geo-synchronous satellites, making a total of 35 satellites. A 12 satellites-system with regional (Asia-Pacific) coverage is planned within a few years from now; the full system with global coverage for 2020. Recently a website has been launched www.beidou.gov.cn, so far only in Chinese language.

Vulnerability of satellite navigation

With four Global Navigation Satellite Systems fully operational by the end of the decade, users on Earth can enjoy signals, at multiple frequencies in the L-band of the Electro-Magnetic (EM) spectrum, from 1.1 to 1.6 GHz, from over 110 satellites. Then there should be, on average, about 30 satellites in view above a 10 degrees elevation anywhere on Earth.

The future of navigation is looking bright, very bright. The above developments provide diversity in system control. There is no single nation that can switch off, or disrupt all systems. There will be many satellites, and there will be substantial diversity in frequency, in terms of the radio-spectrum. This will mitigate risks of interference and jamming. Thereby, satellite navigation starts to play an important role in programs for civil aviation. For instance in Europe, EUROCONTROL, the European Organisation of the Safety of Air Navigation, recently presented its policy, implying a gradually increasing reliance on satellite navigation, based on a multi-constellation and multi-frequency GNSS. More specifically, for Communication, Navigation and Surveillance (CNS), in connection with Air

Traffic Management (ATM), there is a trend and evolution towards 4D trajectory management, for which satellite navigation is an important enabler.

Figure 4: In Safety-of-Life applications as aviation, in particular during critical phases of flight as approach and landing, satellite navigation shall provide a very high level of service. View of the Kaagbaan at Amsterdam Airport Schiphol.

To be used in aviation, in particular during critical phases of flight as approach and landing, satellite navigation shall provide a very high level of service. Correctness, within tight bounds (Alert Limits), of the position solution shall be guaranteed to extremely high levels of probability. In operating an aircraft, the risk of so-called Hazardously Misleading Information (HMI) due to the navigation system is typically budgeted at the 10^{-7} to 10^{-9} level. For Safety-of-Life (SoL) applications as aviation, we quote, as an example, the Galileo SoL core system performance requirements (without receiver contribution) with respect to integrity, as a risk of $2.0 \cdot 10^{-7}$ in any 150 seconds, with an Alert Limit (AL) of 12 m for the horizontal and 20 m for the vertical component.

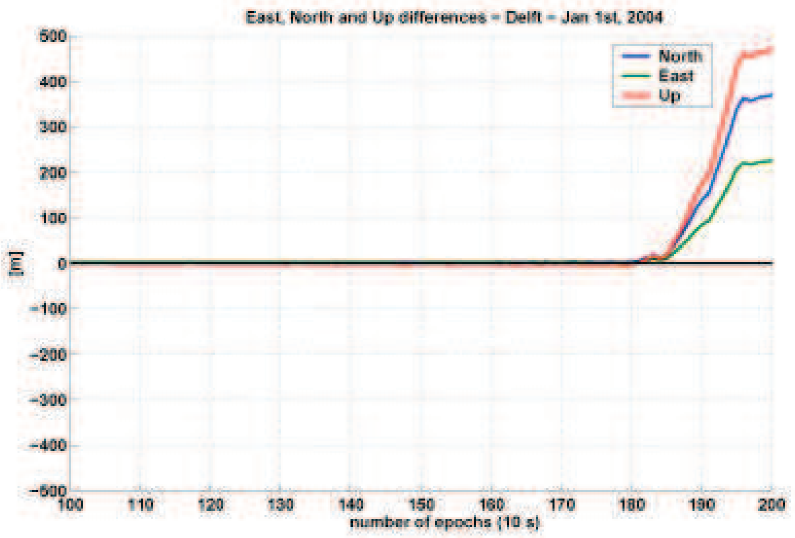
GPS anomaly: case-study

From long term performance monitoring it is known that the GPS does very, very well. But no technical system is perfect. In this case-study we demonstrate that, though the events are very rare, GPS does not always

Figure 5: Though the US GPS has proved to function very reliably, it is *not* however without any failure or anomaly! An actual example will be shown in the next section.

meet the set position accuracy figures. Using a permanently installed receiver and antenna (Trimble 4700 with geodetic chokering antenna) at the TU Delft GNSS observatory, an anomalous event was detected 1 January 2004. The position coordinates of the installation are accurately known and the graph of Figure 6 shows the stand alone position solution (as a user would get), minus the accurately known reference. The position error is expressed in a local East, North and Up frame, to ease interpretation. Almost a 17 minutes time span is shown, from 18h17m to 18h33m (UTC), where the receiver measurement interval was 10 seconds. The position error behaves as expected up to epoch 180, with errors in the order of 5 to 10 meter, whereas in the last three minutes of the graph, the position errors suddenly start to grow to as much as half a kilometer! Around 19h, hence in just half an hour, the position error grows to 15 kilometer. And later the maximum position error became some 70 km without any warning. This shows how satellite navigation can go terribly wrong. Such an event is rare, but can not be completely excluded.

Through analysis it was found that satellite PRN23 was causing the trouble. As can be seen in the so-called skyplot of Figure 6, PRN23 was observed at that time at high elevation. It was almost directly overhead and thereby severely impacting the position solution. The satellite was healthy according to its navigation message. This anomaly impacted satellite navigation performance mainly in Europe and Russia.



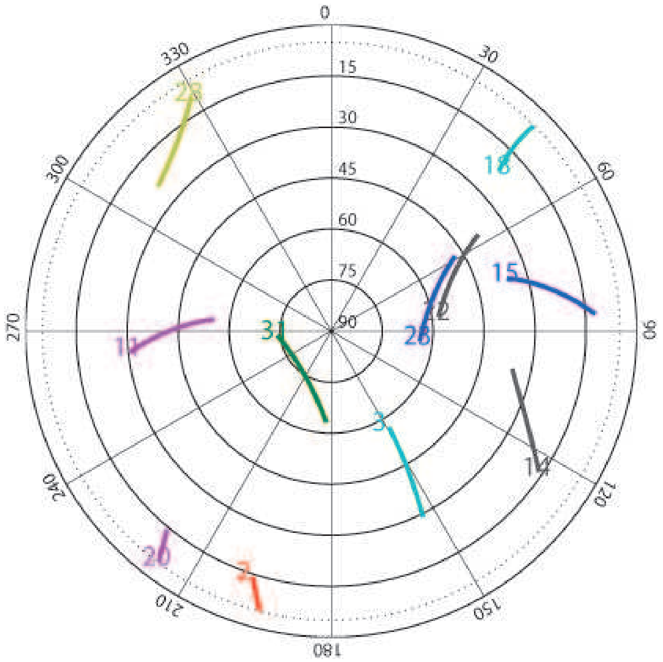


Figure 6: Top: position error expressed in local East, North and Up direction. Bottom: skyplot of GPS satellites, showing azimuth and elevation angles to the satellites, as locally observed in Delft, The Netherlands.

The GPS Support Centre later stated and explained that the anomaly was due to a failed atomic frequency standard (AFS) on SVN/PRN23. A lack of hard failure indications in the satellite telemetry coupled with satellite visibility limitations on the Master Control Station's (MCS) L-band monitor station network made this anomaly difficult to characterize and resulted in the transmission of Hazardously Misleading Information between approximately 18h33m and 21h28m (UTC).

The satellite was not really to blame for this, as this one, a block IIA satellite, was launched on 26 November 1990, and hence at the time of the event, already 13 years old. The satellite was, at that time, out of view from the GPS ground segment stations, so no alarming or corrective action could be undertaken. One month later, this satellite was officially decommissioned from service.

During this event, the position accuracy delivered was definitely not meeting what one usually expects from GPS. In particular when one is not aware of the anomaly and the resulting large bias in position, this could lead to dangerous situations; the GPS receiver says you are at a particular location, but in reality you really are somewhere else.

Actually the performance standards, which the US government commits to provide to civil GPS users, regard an instantaneous so-called Signal-in-Space (SIS) User Range Error (URE) exceeding 30 meter as Hazardously Misleading Information (HMI) when the satellite is set healthy and when the so-called User Range Accuracy (URA) is below a certain threshold. The probability of HMI in the performance standards equals 0.002, resulting from 3 assumed failures per year, lasting no longer than 6 hours each. A probability of 0.2% is still bigger than absolute zero, and it always will be! This means that, though satellite navigation by means of GPS is very, very reliable, nominal performance is *not guaranteed* 100% of the time.

Concluding remarks

What can we do to prevent such failures and anomalies in GNSS? We could deploy an additional network of ground stations in the region of interest, and have the satellite navigation service monitored (and relay alerts and warnings to users in the region). This is referred to as augmentation, and is a means of achieving sufficient integrity at system level. System augmentation still does not cover anomalies and errors in signal propagation and in user equipment.

Using a redundant set of measurements, we could check integrity. In the context of satellite navigation, this is referred to as Receiver Autonomous Integrity Monitoring (RAIM). With, for instance, distances measured to 7 satellites, and only 4 unknown parameters to determine (3 position coordinates and the receiver clock offset), one has three measurements 'too many'. This surplus of measurements can be used to have measurements (partly) checking each other. For instance an unexpectedly large error in only one of them can be detected 'by the others'. Formally this is carried out through statistical hypothesis testing. Doing so on the data of the casestudy immediately leads to PRN23 being detected and identified as the faulty satellite. In an automated way, measurements from satellite PRN23 can be disregarded in the final solution, and the user is provided with a bias-free position solution. The navigation system 'repairs' itself. Adding more systems and more measurements (by using multiple signals and frequencies) is generally beneficial to measurement redundancy, and thus to monitoring performance.

Measurement redundancy can also be enhanced by adding other sensors. For robust and reliable navigation, sensors should be complementary. Different sensors should have different principles of operation and characteristics and different failure modes (with satellite navigation one could think of vision-based positioning and of inertial navigation). In a close integration, all measurements are brought together and processed integrally, thereby exploiting all available measurement redundancy to the maximum. All data are fused to provide one integral position solution. In this sense, adding a back-up system or sensor is just a rudimentary form of sensor integration, as one effectively uses the back-up, only in case of the primary sensor failing.

Further Reading

In this article the current status and development of GNSS has been discussed. Of course, besides this overview, many interesting articles and textbooks exist on the topic for further reading. Here, we would like to mention a few.

A decent, up-to-date textbook on satellite navigation is the book by Misra & Enge [1], that deals with several topics to do with GPS, like GPS signals, GPS receivers and measurements. For the Glonass system a presentation by Kovenko [2], at the 2009 European Navigation Conference last year, gives a good overview of the current status and plans. Concerning aviation issues, the Eurocontrol policy on GNSS is well described in [3]. Furthermore, integrity with (satellite based augmented) satellite navigation, in the context of (civil) aviation, is discussed in [4].

References

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