ESPOO 2007 VTT RESEARCH NOTES 2408

Paul Kemppi

Next generation satellite navigation systems

VTT TIEDOTTEITA – RESEARCH NOTES 2408

Next generation satellite navigation systems

Paul Kemppi

ISBN 978-951-38-6961-8 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0865 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 3, PL 1000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4374

VTT, Bergsmansvägen 3, PB 1000, 02044 VTT
tel. växel 020 722 111, fax 020 722 4374

VTT Technical Research Centre of Finland, Vuorimiehentie 3, P.O.Box 1000, FI-02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 4374

Technical editing Leena Ukskoski

Text preparing Kirsi-Maarit Korpi

Kemppi, Paul. Next generation satellite navigation systems Espoo 2007. VTT Tiedotteita – Research Notes 2408. 61 p. + app. 2 p.

Keywords satellite navigation systems, global positioning systems, augmentation systems, pseudolites, A-GPS, A-GNSS, system architecture, cellular networks, GNSS, mobile wireless communication

Abstract

The report gives a brief introduction to the existing and planned global satellite navigation and augmentation systems. It addresses their current status and future modernisation / development plans in addition to their basic architecture. The report also presents the idea behind pseudolites and the challenges related to them. Furthermore, the convergence of global satellite navigation systems and wireless communication devices is covered by explaining the concepts of A-GPS and A-GNSS. The two architectural approaches to implement A-GPS are discussed as well as the modifications required to the cellular network specifications introduced by next generation GNSSs. Information sources related to satellite navigation and positioning including universities, research institutes, organizations, agencies, magazines and relevant projects are also collected to this document in order to create a knowledge base of the research field. Finally, issues that affect the evolution of satellite based positioning are being discussed.

Contents

1. Introduction

Satellite based positioning is becoming increasingly important in our lives. Already now, it is used in many sectors of transport, security, surveillance, industry, research, and leisure. Numerous safety-of-life applications are dependent on reliable and accurate location provided by the existing global navigation satellite systems (GNSS). At present, the US Global Positioning System (GPS) has effectively a monopoly in providing a global localization service. This situation is, however, about to change: Russian GLONASS is being revitalized after a long period of degradation. In addition, the European Union (EU) together with the European Space Agency (ESA) has agreed to build its own GNSS named as Galileo. China has also announced to continue elaborating its regional Beidou navigation system. It's expected to be expanded providing eventually a global coverage. Moreover, India and Japan are also establishing their own systems to complement and augment existing and future global satellite navigation systems.

The idea behind satellite based positioning is rather simple: If the distances from a point on the Earth to three orbiting satellites are known along with the satellite locations, then the location of the point can be determined by applying the concept of resection [27]. In practice, a fourth satellite is needed to account for the receiver clock offset [47]. The location estimation process is affected by various error sources including ionospheric and tropospheric delays, multipath propagation, satellite clock errors, receiver noise and resolution, and errors in predicting the navigational model of the satellites [48]. In addition, the availability of the positioning service is mainly restricted to places having direct line of sight to the orbiting satellites. The new satellite navigation and augmentation systems try to overcome these limitations and provide a reliable, accurate position and timing services at any time and at any place in the world.

The readers of this report are assumed to have a basic understanding of the principles and concepts related to satellite based positioning. A comprehensive introduction to the fundamentals of GPS can be found e.g. in [24]. An elaborate analysis of the GNSS error sources and their detection is presented in [48].

The aim of this report is to give an overview of the existing and planned satellite navigation systems, augmentation systems and pseudolites (Chapters 2–4). In addition, Chapter 5 is devoted to the convergence of GNSSs and wireless communication devices. It is expected to be one of biggest emerging application areas for satellite based positioning. The required modifications to the cellular network specifications introduced by next generation GNSSs are presented as well as the concepts of A-GPS and A-GNSS. Chapter 6 is meant to be a starting point for satellite navigation and positioning knowledge base. Information sources including universities, research institutes, organizations, agencies, magazines and relevant projects are collected to this document. Later on, this information will be moved to a TWIKI page that can be more easily updated and reviewed. Finally, Chapter 7 discusses various aspects of the present turning-point of satellite based positioning by assessing the factors that affect the way satellite navigation and positioning will evolve in the near future.

2. Global navigation satellite systems

Currently, there are only two operational navigation satellite systems having global coverage: American Global Positioning System and Russian counterpart GLONASS. Galileo will be the third GNSS but it is still in orbit validation phase. In addition, China is planning to expand its own satellite navigation system Beidou into GNSS [16]. So far it provides only regional coverage. Indian Space Research Organization (ISRO) has also announced plans to build an independent navigation satellite system. However, its space segment will only consist of seven or eight satellites. It is called Indian Regional Navigation Satellite System (IRNSS) and it is estimated to be operational in 2011–2012 [18].

2.1 Global Positioning System (GPS)

In 1973, US Navy and Air Force joined together to develop a first satellite based navigation system called Defence Navigation Satellite System (DNSS). The project was later renamed as NAVSTAR. Its first test satellite was launched in 1978 and first operational satellites were sending signal in 1989. In 1993 the program achieved its initial operational capability and a year later, full operational capability was attained [29].

2.1.1 System architecture and current status

The Global Positioning System consists of space, control and user segments. The space segment comprises of satellites transmitting the navigation signals to the user segment. The control segment is composed of a worldwide network of tracking stations and the Master Control Station (MCS) located at Colorado Springs, Colorado. The tracking stations are used to determine and predict satellites' locations, monitor their atomic clocks and system integrity. This information is sent to MCS, which then produces update messages for each GPS satellite regularly. Based on these updates, satellites will then synchronize their atomic clocks and adjust the internal orbital model. The user segment includes both military and civilian user equipment [24].

The space segment of GPS has already comprised four generations of satellites. The Block I satellites were used to test the principles of space based position, analyze the orbital circumstances etc. Since 1997 Block IIR satellites have started to replace older Block II and IIAs. They have reprogrammable satellite processors enabling in flight problem fixes and upgrades. The first modernized Block IIR (designated as the IIR-M) with L2C was launched in the 26th of September 2005. The newest and third consecutive Block IIR-M satellite was activated in the 13th of December, 2006.

Currently, as in the 28th of May 2007, the GPS constellation consists of 30 satellites including 15 Block IIA, 12 Block IIR and 3 Block IIR-M spacecrafts [51]. The next launch is expected to take place around summer 2007 [33].

The GPS satellites are orbiting at an altitude of approximately 20200 kilometres above Earth's surface. They are distributed among six orbital planes having approximately 55° inclination to geostationary orbit and orbital period of 11 hours and 58 minutes. The satellites were originally designed to broadcast signals in two frequency bands (L1 centred at 1575.42 and L2 centred at 1227.60). L2 signal consists of an encrypted P(Y)-code for US military purposes. L1 signal is a mix of encrypted P(Y)-code, coarse-acquisition code (C/A-code) and Navigation Message. The C/A code is a 1,023 bit long pseudo-random code broadcast at 1.023 MHz, repeating itself every millisecond. Each satellite has a distinct C/A code, which can be used to identify the source of signal. The P-code is a similar code broadcast at 10.23 MHz, but it repeats itself only once a week. P code is encrypted into the P(Y)-code, which can only be decrypted by units with a valid decryption key [24].

2.1.2 Modernisation

Lockheed Martin has announced the delivery of the eighth and final satellite in the modernized GPS IIR-M production program to the Air Force. There are currently three operational IIR-M satellites, and the fourth one has been delivered to Cape Canaveral to support a late 2007 launch. The remaining satellites are kept in storage and are available for launch when requested by the Air Force [37]. According to [40], an Air Force commander has informally told GPS World that the GPS Wing has prepared a plan to boost all remaining IIR-M satellites into orbit during within 2007.

The new Block IIR-M satellites are a part of plan to modernize the GPS in order to meet the increasingly demanding needs of the new applications. However, the older Block IIR (replenishment) satellites built by Lockheed Martin are proving remarkably durable. They haven't had any failures in the nearly 10 years since the first one was launched in July 1997. Also the older Block IIA and Block II built by Boeing have had longer than expected life span. The durability past the original life expectancy of the satellites has complicated the modernisation of the GPS system [33]. Originally it was planned that the next step in the GPS modernisation process after Block IIR-M satellites would be to launch 33 Boeing's Block IIF (follow-on) satellites. However, due to the current 'launch on need' policy; this number has been reduced to 12–16 satellites [33]. Block IIF satellites are the next generation of GPS space vehicles. They provide all the capabilities of the previous blocks with some additional benefits. Improvements include an extended design life of 12 years, faster processors with more memory, and a new civil signal [39]. The first Block IIF satellite is scheduled to launch in May 2008 [40].

According to [33], the current ‘launch on need’ policy may change with Block III program, which is the follow-up for Block IIF reform. In April 2007, Boeing and Lockheed Martin provided their Block III system design reviews for evaluation. The reviews validate the detailed design of the next big step of GPS to ensure that it meets military and civil user requirements. The Air Force is expected to award a multi-billion dollar development contract to a single contractor team in late 2007 [37].

Besides the introduction of new satellites, the modernisation process involves renovation of the ground segment and introduction of four additional navigation signals. The three new civilian signals are called L2C, L5 and L1C, and the new additional military code is called M-code (see Figure 1). The three recently launched Block IIR-M satellites already transmit the new civilian signal L2C and M-code. For instance, researchers at Satellite Navigation and Positioning Lab in University of New South Wales have managed to acquire the signal successfully [50]. M-code has also been turned on but Air Force will not guarantee its availability or quality until Initial Operational Capability (IOC) [41].

Although the L2C signal is already available, the value of this signal to the civil user community will emerge only after additional Block IIR-M satellites are introduced into the constellation. L2C enables the development of lower-cost, dual-frequency civil GPS receivers that allow for correction of ionospheric time delay errors. After the modernisation of control segment is complete, enhancements such as dataless and pilot channels for improved performance and an improved navigation message with more precise clock and ephemeris information will be available. L2C will also be interoperable with the Quasi-Zenith Satellite System (QZSS) [39].

According to [42], L2C signal has remarkably poorer acquisition performance compared to L1 C/A-code. Thus, the dual L1/L2C receivers should be designed to acquire L1 first and then hand over to L2C. On the other hand, the dataless L2C CL code will be easier to acquire than L1 C/A in an environment where signals are heavily attenuated. Acquiring position fix in weak signal environment is easier with L2C CL because it has superior cross-correlation properties for long integrations. This means that other strong L2C signals are much less likely to prevent the weaker signal from being acquired.

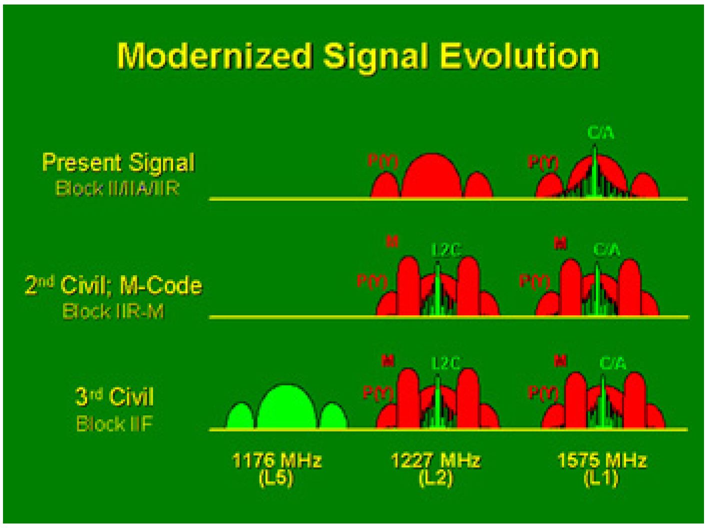

Figure 1. Evolution of GPS signal scheme [38].

In addition to L2C, Block IIF satellites will introduce another civil signal L5, which aimed especially for safety-of-life aviation. L5 will transmit at a higher power than current civil GPS signals, and have a wider bandwidth. Its lower frequency may also enhance reception for indoor users [39]. Yet another new civil signal will be introduced along Block III satellites: L1C (centred at 1575.42 MHz) will be backward compatible with the current civil signal on L1. It will be broadcasted at a higher power level, and include advanced design for enhanced performance [39].

For civil users, the new signals provide more robustness against interference, compensation for ionospheric delays and assistance to resolve integer ambiguities caused by cycle slips during precise carrier phase measurements. For military users, the new spectrally separated signals provide protection for friendly use, prevention of adversary exploitation and preservation of civil use outside area of operations [43].

2.2 Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS)

Four years after the first GPS prototype satellite was launched by the Unites States, the first GLONASS satellites were placed in orbit by the former Soviet Union. The original plan was to have a complete operational system by 1991, but the deployment of the full constellation of satellites was not finished until the turn of the year 1996. GLONASS was officially declared operational in the 24th of September, 1993 by a decree of the President of the Russian Federation. Nowadays, GLONASS is managed for the Russian Federation Government by the Russian Space Forces. The system is operated by the Coordination Scientific Information Centre of the Ministry of Defence of the Russian Federation [44].

2.2.1 System architecture and current status

Currently, as in the 28th of May 2007, the GLONASS constellation consists of 17 satellites. 7 satellites are temporarily switched off and one satellite is in commissioning phase [52]. The satellites reside in 3 orbital planes. The orbital planes are separated 120 degrees from each other. The satellites operate at an altitude of approximately 19100 kilometres above Earth's surface. The orbital planes have inclination angle of 64.8 degrees and each satellite completes a full cycle around Earth in approximately 11 hours 15 minutes [44].

Like GPS, GLONASS satellites transmit two L-band carriers that contain military P-Code on both L1 and L2, C/A-code on L1, and a navigation message. In contrast to GPS, the GLONASS satellites transmit the same C/A-code using their own carrier frequencies. L1 carriers are in the bands between 1,597–1,617 MHz and L2 carries between 1,240–1,260 MHz. Thus, GLONASS uses Frequency Division Multiple Access (FDMA) instead of Code Division Multiple Access (CDMA) to distinguish the satellites. The chipping rates for the P-code and the C/A-code are 5.11 and 0.511 Mbps, respectively and the navigation message is a 50-bps data stream, which provides, among other things, the satellite ephemeris and the channel allocation [57].

The control segment of GLONASS is entirely located within former Soviet Union territory. The Ground Control Centre and Time Standards are located in Moscow and the telemetry and tracking stations called Receiving Monitor Stations (RMS) are in St. Petersburg, Ternopol, Eniseisk, and Komsomolsk-na-Amure [44].

During the recent years, GLONASS has had reliability problems with its satellites and it has been struggling to provide global service. The ground segment of GLONASS offers poorer integrity monitoring than the GPS. A GLONASS satellite can be broadcasting erroneous data for up to six hours before it is detected by the GLONASS ground segment and reported to be unhealthy [45].

Despite the fact that GLONASS has not been able stand on its own for satellite positioning, it still has appeared to be quite useful for dual system (GPS + GLONASS) receivers. Especially for the users of Real Time Kinematic GPS (RTK-GPS), a receiver that can use GLONASS satellites to augment the GPS position has proven to be highly advantageous in an environment having a poor satellite visibility [45].

2.2.2 Modernisation

Fuelled by the enormous oil and natural gas resources, Russia's space program has been recovering from its degradation. As a result, GLONASS could be transformed into a commercial system capable of competing in mass markets for GNSS user equipment [33]. In January 2006, the president of Russia, Vladimir Putin announced a directive to have 18 operational GLONASS satellites in place by the end of 2007 and 24 by 2009. The directive also declared that the performance of GLONASS will be comparable with GPS by 2009 [46].

Only seven of the currently orbiting GLONASS satellites are enhanced GLONASS-M satellites. The rest of the constellation consists of spacecrafts that are closing their expiration date. This might force Russia to launch 17 new satellites by the end of 2009 to keep its declared schedule [67].

According to [46], the planned improvements include two new civil signals at L2 and L3 frequency bands. The new civil signal at L2 frequency band is already broadcasted by the GLONASS-M satellites. It is expected to provide higher positioning accuracy. The third civil signal will be added to the signal scheme along with the GLONASS-K satellites scheduled for launch in 2008. L3 signal will provide higher reliability and accuracy and is especially intended for safety-of-life applications as it will provide GNSS integrity information to guarantee the reliability of the navigation service. It will also offer global differential ephemeris and time corrections in order to provide sub-meter real time accuracy for mobile users. Both the space segment and control segment will be modernized: e.g. satellite clock's stability will be improved and the network of Receiving Monitor Stations (RMS) will be extended [46].

GLONASS satellites may also start using CDMA signals in addition or even in place of the system's FDMA signals. The decision in this regard is presumably made by the end of year 2007 [33]. The use of CDMA would remarkably ease the dual use of GPS and GLONASS and facilitate manufacturer of combined receivers [67].

2.3 Galileo

Even after the unveiling of US Government's first plans to build the modernised GPS III system in 2001, the authorities in Europe considered the GPS as systems that lacks service guarantee and accountability. Thus, the European Union (EU) together with the European Space Agency (ESA) decided to develop of system of its own that provides better performance in terms of accuracy, reliability and security [53].

Galileo is a joint initiative led off by EU and ESA. EU is responsible for the political dimension of Galileo and for setting objectives for the development program. ESA is liable for the technical definition, development and the validation of Galileo. A governing body called the Galileo Joint Undertaking (GJU) was formed to manage the development phase of the Galileo Programme. The GJU is overseeing the establishment of a partnership between the public and the private sector in order to mobilise the required funds for the project. In addition, GJU is also managing EU's 6th Framework Programme for Research and Development (FP6) in Galileo related activities [66].

2.3.1 Service levels

Galileo will offer five different service levels in terms of accuracy, integrity and reliability. The Open Service (OS) is free for any user equipped with a receiver capable of tracking one or more of the signals transmitted on the E5a, E5b and E2-L1-E1 carriers [58]. The OS offers neither integrity information nor any service guarantees [53].

The Safety-of-Life Service (SoL) is indented for e.g. transport applications where lives could be endangered in case of sudden increase in positioning error. The accuracy of the SoL is equal to OS but it offers worldwide high integrity level and fast alert mechanism. The SoL service will be available for users equipped with certified dual-frequency (L1 and E5) receivers. The Commercial Service (CS) is aimed at applications requiring higher performance than offered by the OS. CS utilizes two additional signals E5b and E6 [58] together with OS signals to achieve better performance. The additional signals are encrypted and access is controlled at the receiver level via access-protection keys [53].

The Public Regulated Service (PRS) will be used by government-authorised groups such as the police, coastguard and customs. The PRS will give extra protection against jamming and spoofing. The Search and Rescue Service (SAR) is meant to be used in rescue operations providing increased availability by using four Low Earth Orbit (LEO) and three geostationary satellites (COSPAS-SARSAT system) in addition to MEO constellation. Besides increased availability, the SAR includes near real-time reception of distress messages from anywhere on Earth [53].

2.3.2 Architecture

Galileo's space segment will consist of 30 satellites in Medium Earth Orbit (MEO) at about 23,222 km altitude completing the revolution around the Earth in about 14 hours. Satellites are spread evenly over three orbital planes inclined at 56° to the equator. Each plane contains one spare satellite that can be use in case of malfunction in some of the operating satellites. After achieving the initial operational capability, further launches will be carried out to replenish the constellation and replace the depleted satellites [53].

Galileo's control segment will include a network of sensor stations, two control centres and uplink stations. The worldwide sensor station network will monitor continuously the constellation and send its precise measurements of the navigation signals to the two control centres residing in Europe. The orbits and clock data produced by the control centres will be sent to the uplink stations to be uploaded to the satellites about every 2 hours. The control centres will also estimate the integrity of the constellation and provide frequently the associated data to the users of Safety-of-Life service. In the case of e.g. malfunctioning signals, the system will be able to alert the users with a delay of only 6–10 seconds. Regional service providers can also utilize their own sensor networks to monitor the integrity of Galileo signals. The data can be made available for the users either via authorised integrity uplink channels of the Galileo satellites or centrally via Galileo control centres [53].

2.3.3 Signal scheme

Galileo satellites will transmit 10 different signals. Six of them will serve open and safety-of-life services. Two are for commercial services and two are for public regulated services. Signals will be broadcasted in the following frequency bands:

- E5A-E5B (1164-1215 MHz)
- E6 (1260-1300 MHz)
- E2-L1-E1 (1559-1591 MHz).

The navigation signals will consist of ranging codes and data messages. In addition to satellite identity, clock and navigational model information, the data messages will include a Signal-In-Space Accuracy parameter predicting the satellite clock and ephemeris accuracy over time. The data messages may also include regionally or globally determined integrity data [53].

2.3.4 Current status

Galileo System Test Bed Version 1 (GSTB-V1) experimentation was completed in the 22nd of December 2004 after twelve months of successful ground segment development. The GSTB-V1 included a worldwide network of sensor stations that were used to collect high quality GPS observables at 1 Hz. In addition, it was using an experimental Precision Timing Station (PTS) to provide the reference time scale steered to universal time and international atomic time (UTC/TAI), and a processing centre located at the European Space Agency to generate navigation and integrity core products based on Galileo-like algorithms [61].

GJU has started to launch through ESA a first series of satellites to ensure the large-scale demonstration of the capabilities and reliability of the Galileo system. This phase is called Galileo in Orbit Validation (GIOVE). The first satellite named as GIOVE-A was launched successfully in the 28th of December 2005. The objective of the mission is to secure the frequency filing, measure MEO environment, demonstrate key payload technologies, and provide signal-in-space for experimentations [62].

The GIOVE-A has been operating as expected but the launch of the follow-up satellite, GIOVE-B, has been postponed several times albeit it was originally scheduled to be launched in April 2006 [64]. One of the reasons for the delay was a short circuit occurred during final testing in Italy [65] but the disagreements inside the Galileo operating consortium have caused even more lag [59].

According to [60], the Public-private partnership (PPP), established by GJU in order to mobilise the required funds for the Galileo project, was laid to rest in Brussels in the 16th of May 2007. However, the EU Industry Commissioner Guenter Verheugen ruled out cancelling Galileo. "Galileo is from the European Commission standpoint an absolutely essential project," he stated. "We don't have an option of giving up on Galileo."

2.4 Compass (Beidou-2)

The first two test satellites (BNTS-1 and Beidou 1B) of China's regional navigation satellite system were launched in 2000 into geostationary orbits (located at 140°E and 80°E respectively). They were followed by Beidou 1C satellite in 2003 (110.5°E). The Beidou satellite system currently functions as a regional positioning system for survey, telecommunications, transportation, meteorology, fire alert, disaster forecast, and public security [16].

In the 2nd of February 2007, fourth satellite was launched into its geostationary transfer orbit. The satellite reportedly had a problem with a stuck solar panel, which needed to be fixed before the satellite could be moved to its intended geostationary location. The fifth satellite was launched in the 13th of April, 2007. The initial orbital elements (inclination = 55.0°, eccentricity = 0.62, mean motion = 3.84 orbits per day) may indicate that this is not another geostationary satellite but rather the first of the Medium Earth Orbit (MEO) satellites [15].

China's state press agency Xinhua announced in the 2nd of November, 2006 that the country plans to build an enhanced regional satellite navigation system that will attain operational status in the Asian region by 2008. The existing Beidou systems will be expanded to 5 geostationary satellites and 30 MEO satellites having eventually a global coverage. This new GNSS will be known as Compass [16].

3. Augmentation systems

The idea of an augmentation system is to reduce or eliminate factors that deteriorate the quality of position, navigation and timing services based on GNSS signals [30]. Augmentation systems can be divided into the following two categories depending on how the augmentation information is broadcasted to the receivers: Ground Based Augmentation Systems (GBAS) and Satellite Based Augmentation Systems (SBAS).

3.1 Ground based augmentation systems

GBAS is a system that provides augmentation messages through the use of terrestrial radio network. GBAS uses augmentation information provided by a network of ground based reference stations. These reference stations are used to monitor GNSS signals and determine the error components including satellite ephemeris errors and those introduced by ionospheric and tropospheric disturbances. Ground based augmentation systems can be divided into subcategories based on the scale of the reference network and purpose of use.

3.1.1 Local Area Differential GPS

Local Area Differential GPS services improve the accuracy of GPS by placing high quality reference receivers into known, surveyed locations. These reference stations estimate the slowly varying error components of each satellite's range measurements, formulate the differential corrections and broadcast them to local users e.g. on commercial AM frequencies. The performance of Local Area DGPS receivers degrades as the distance from the reference receivers increases. Local Differential GPS is mainly utilized by the maritime vessels and national coast guards. For instance, the local DGPS network of Finland is developed and maintained by Finnish maritime administration in order to improve the safety on the fairways of the Baltic Sea and inland waterways [11].

3.1.2 Wide Area Differential GPS

In Wide Area Differential GPS (WADGPS), a broad network of reference stations is used to form a vector correction for each satellite [2]. The vector consists of individual corrections for the satellite clock, ephemeris and ionospheric delay model. The vector correction is valid over much broader geographical area than Local DGPS corrections.

One of the WADGPS implementations is the patented Global Differential GPS System (GDGPS) provided by NASA’s Jet Propulsion Laboratory (JPL) [1]. It is a complete, highly accurate, and extremely robust real-time GPS augmentation and monitoring system. GDGPS employs a large ground network of real-time reference receivers (over 70 reference stations) to track the GPS civil signals on the L1 and L2 frequencies. The measurements from the reference receivers are streamed via redundant communication paths to GDGPS Operation Centres (GOC) (3 centres as of October 2006) to be processed into the real-time differential corrections. The GDGPS System provides decimetre (10 cm) positioning accuracy and sub-nanosecond time transfer accuracy anywhere in the world. However, in the low latitude, and during ionospheric storms the positioning error may be notably worse [1].

3.1.3 Local Area Augmentation System (LAAS)

Similarly to Local Area DGPS, LAAS is based on differential correction of the GPS signal and use of local reference receivers. LAAS was developed by the US Federal Administration of Aviation (FAA) to provide an all-weather precision navigation approach and landing capability within a nominal 37km area around airports [12]. The ground system broadcasts differential GPS corrections and integrity messages via VHF radio data link. LAAS offers precise positioning information of the nearby aircrafts that can be used by surface surveillance systems to prevent accidents in landing during low visibility conditions.

3.2 Satellite based augmentation systems

Similarly to ground based augmentation systems, satellite based augmentation systems are used to augment GNSS signals. Currently, there are three operational regional satellite based augmentation systems in North America, Europe and Japan. India is also developing its own satellite based augmentation system. The augmentation data provided by the existing systems can be freely utilized with a GPS receiver that supports SBAS messages. Many of the latest GPS receivers already support SBASs. For instance, Insmat SiRFIII Bluetooth GPS supports both Wide Area Augmentation and European Geostationary Navigation Overlay Service (see Figure 2). In addition to the freely available SBASs, commercial solutions also exist for various purposes. They require subscription and an advanced receiver but provide better accuracy and global coverage.

Figure 2. Insmat SiRFIII Bluetooth GPS with WAAS/EGNOS support.

3.2.1 Wide Area Augmentation System (WAAS)

The Wide Area Augmentation System is a satellite based augmentation system developed originally for civil aviation by the Federal Aviation Administration (FAA). It provides augmentation data for users in the United States and its neighboring areas. The system consists of a network of ground stations named as Wide-area Reference Stations (WRS), two terrestrial Wide-area Master Stations (WMS) and four geostationary satellites: POR (PRN 134, 178°E), AOR-W (PRN 122, 142°W), Galaxy XV (PRN 135, 133°W) and Anik F1R (PRN 138, 107°W). The last two satellites are not yet fully integrated into the system [23].

The ground stations of WAAS are located throughout North America, Hawaii and Puerto Rico to measure constantly the GPS signals and send measurements to the two master stations. The two master stations then generate and send correction messages via Ground Uplink Stations (GUS) to the geostationary satellites, which broadcast them back to the Earth for the WAAS-enabled GPS receivers [23].

The WMSs generate both fast and slow corrections. The fast corrections concern GPS satellites' position and clock errors. These errors are independent from receivers' position, so they can be corrected rapidly. The slow corrections try to correct errors caused by ionospheric delay and errors related to long term ephemeris and clock drift. The ionospheric delay corrections are provided for a number of points (organized in a grid pattern) across the WAAS service area. WAAS augmentation increases the positioning accuracy of GPS from 20 meters to approximately 1.5–2 meters in both the horizontal and vertical dimensions. Availability is also improved through the addition of the WAAS satellites providing extra course correction data. WAAS also eliminates the requirement to conduct receiver autonomous integrity monitoring (RAIM) predictions. In terms of safety, WAAS provides pilot alerting within 6 to 8 seconds (depending on the airborne equipment) whenever the input signal for positioning becomes unusable [23].

3.2.2 European Geostationary Navigation Overlay Service (EGNOS)

The European geostationary navigation overlay service provides augmentation information for the US GPS and the Russian counterpart GLONASS signals in Europe region. The wide area differential corrections of EGNOS improve the positioning accuracy of GPS L1 signal down to less than two meters [25]. In addition to wide area differential corrections, EGNOS provides integrity information to notify adequately equipped receivers about any malfunction of the GNSS or their satellites. As the wide area differential corrections are modulated onto the GPS L1 frequency, the EGNOS satellites will also improve the availability of the GPS L1 signal by increasing the number of satellites broadcasting the L1 signal [13].

Currently, there area three active EGNOS satellites: IOR-W (PRN 126, 15.5°E) and AOR-E (PRN120, 65.5°E) provide the wide area differential corrections to the public users. The third satellite called ARTEMIS (PRN 124, 21.5°E) is currently used by industry to perform various tests on the system [13]. The ground segment consists of ~40 reference stations distributed throughout Europe [25].

The ground segment of EGNOS consists of 34 Ranging and Integrity Monitoring Stations (RIMS), which are connected to 4 Mission Control Centres (MCC). MCCs are redundant control and processing facilities that determine the integrity and pseudo-range differential corrections for each monitored satellite. In addition, they quantify ionospheric delays and generate ephemeris data for the EGNOS satellites. All this information is sent in a form of message to a Navigation Land Earth Station (NLES) to be forwarded to the geostationary satellites [31].

The predecessor of EGNOS was called EGNOS System Test Bed (ESTB). It was a reduced version of EGNOS using experimental monitoring stations and processing centres. It provided a possibility for the device manufacturers and application developers to test and validate their products in a realistic environment. ESTB was declared operational in 2000. EGNOS grew parallel with ESTB transmitting its first signal already in 2003. In 2006 ESTB was discontinued after serving well its purpose of being the first European satellite based navigation system [25].

3.2.3 MTSAT Satellite Based Augmentation System (MSAS)

MSAS is based on Multi-Functional Transport Satellites (MTSAT) built by Mitsubishi Electric and operated by the Japan Civil Aviation Bureau. It is a predecessor of Japan's Quasi Zenith Satellite System. The first MTSAT-1R satellite was launched in 2005 and was followed by MTSAT-2 in 2006. These two satellites will assist air traffic management by augmenting GPS similarly to WAAS and EGNOS. The operational area covers the eastern Asia and western Pacific regions. The satellites reside in geostationary orbit (140°E & 145°E) [17].

3.2.4 Quasi Zenith Satellite System (QZSS)

Japan began to build its own regional navigation satellite system in 2003. The project is called Quasi-Zenith Satellite System and its goal is to complement and augment GPS. The QZSS consists of three satellites, which will provide communication and broadcasting services in addition to localization. All the three satellites will have their own separate orbit plane, which inclination is around 45 degrees to the geostationary orbit (GEO). The orbit planes are designed in such a way that there is always at least one satellite around the zenith for about eight hours in mid-latitude area over Japan. This is beneficial especially in urban areas containing many high-rise buildings and narrow street canyons. The launch of the first satellite was planned to take place in 2008 but is being postponed until at least 2009 [17].

QZSS will be fully compatible and interoperable with current and modernized GPS. The frequency plan for QZSS is depicted in Figure 3. It will consists of L1 (1575.42MHz), L2 (1227.60MHz) and L5 (1176.45MHz) signals. The signal called L1-Sub meter class Augmentation with Integrity Function (L1-SAIF) will provide WDGPS correction message based on SBAS message format adding to above mentioned GPS interoperable signals on L1 band. Moreover, LEX signal on E6 (1278.75MHz) will be transmitted for experimental and augmentation mission [32].

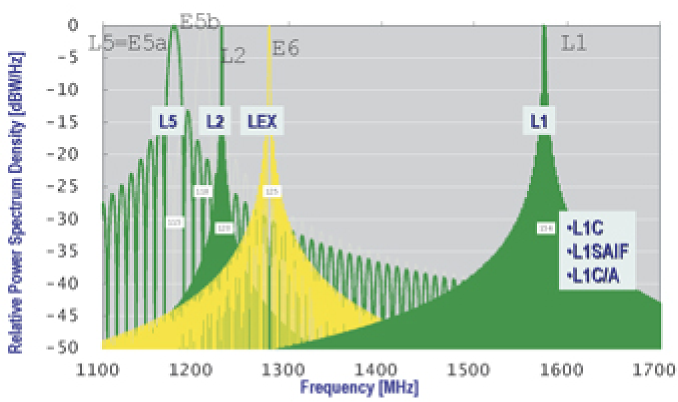

Figure 3. Frequency plan for QZSS navigation signals [32].

3.2.5 Geostationary Earth Orbit Augmented Navigation (GAGAN)

The Indian Space Research Organization is developing a satellite based augmentation systems for civil aviation with the Aviation Authority of India. The system is named as Geostationary Earth Orbit Augmented Navigation. The space segment will consist of India's GSAT-4 satellites. In addition to GSP L1 signal, GAGAN will also broadcast the new safety-of-life signal L5. The ground segment consists of eight Indian reference stations, a master control centre, a land uplink station and associated navigation software and communication links [18]. India and the US have signed a joint statement to facilitate broad and effective use of WAAS and GAGAN as civil space-based regional augmentations to the GPS [20].

3.2.6 OmniSTAR

OmniSTAR provides various positioning solutions including Virtual Base Station (VBS) technology for sub-meter level positioning, dual-frequency GPS augmentation service for decimetre level positioning and monitoring & tracking services. Its ground segment consists of approximately 100 reference stations, 14 satellite uplinks and 2 global network control centres. OmniSTAR's space segment includes 9 satellites [14].

3.2.7 StarFire

NavCom Technology Inc. has developed a global satellite based augmentation system that provides decimetre level positioning accuracy on a worldwide basis. According to its website [21], NavCom is the only GPS manufacturer providing both GSBAS signal service and high-precision GPS products of its own design. The StarFire global subscription service provides real-time accuracy, which is normally better than 10 cm. Its globally corrected signal is available virtually anywhere on the Earth's surface on land or at sea, from 76ºN to 76ºS latitude. The system utilizes a network of more than 60 GPS reference stations around the world and three geostationary satellites to broadcast the real time corrections to the users around the world. Since 2001, NavCom has cooperated with NASA's Jet Propulsion Laboratory to combine JPL's GDGPS together with StarFire [21]. NavCom offers two types of StarFire subscription licenses: Land Only (excludes all oceans/offshore) and All Areas (global coverage).

3.2.8 VueStar

VueStar is a complete global satellite based augmentation system that is configured specifically for all aerial survey applications developed by NavCom Technology Inc. It utilizes the global satellite based StarFire network to provide precise positioning worldwide without the need for RTK base stations or GPS post processing [22].

4. Pseudolites

Pseudolites (pseudo satellites) are ground based transmitters that generate and transmit GNSS compatible signals. Pseudolites can be placed in locations that have poor satellite visibility to improve availability and accuracy of GNSS based positioning. In an indoor space where the GNSS signals are heavily attenuated, a set of pseudolites can be even used to replace the whole GNSS constellation (see Figure 4).

Figure 4. LocaLite (pseudolite) antenna used in indoor positioning trial at UNSW Snap Lab.

Pseudolites have several benefits compared to a pure satellite based system: They can be deployed without hardware modifications to the GNSS receiver and only minor changes are required to the receiver firmware [35]. The number and locations of the pseudolites can also be adjusted according to the environment to improve both the vertical and horizontal dilution of precision and thus, to maximize the performance of the system. Moreover, as being ground based transmitters, pseudolites are not affected by the ionosphere, which is the major source of error in GNNS based positioning [24].

Pseudolites have also weaknesses: One of them is called the near-far problem. It is caused by the variation in the received signal power of the pseudolites when the distance between the receiver and the transmitters changes. A pseudolite in the vicinity of receiver may overwhelm the signals from other pseudolites/satellites and jam the receiver. On the other hand, if some of the pseudolites reside too far, their signal level may be too weak to allow the receiver to detect them. Transmitting the pseudolite signal in short pulses with a low duty cycle can be used to minimize the effect of the near-far problem [36].

In order to set up a pseudolite system, the accurate locations of the transmitters have to be measured and defined. This can be a challenging task especially if the system is planned to be built quickly or in a place where there is no other way to define locations than measuring distances from a known location (e.g. in indoor spaces and drift mines). In addition, multipath propagation of the signal deteriorates the accuracy especially in an environment having plenty of reflecting surfaces [35]. The transmitter itself can also cause multipath propagation.

Pseudolites are usually equipped with low-cost crystal clocks in order to reduce their unit price. These inaccurate clocks drift and therefore decrease the positioning accuracy. This problem is overcome by deploying a master station that has more precise clock. The master station will keep the pseudolites in time by sending synchronization messages to them [24].

Pseudolites are mainly used in places where real-time positioning at centimetre-level is required. Automating the heavy and expensive mining machines in open-pit mining has been one of the major applications [34]. It should be noted that if pseudolites are e.g. transmitting L1 signal, they can jam real GPS L1 signals, denying GPS service to nearby receivers that are not configured to measure signals transmitted by pseudolites [35].

5. GNSSs & mobile wireless communication

The integration of satellite navigation receiver into a mobile wireless communication device is predicted to be one of the driving forces behind the LBS markets. Already now, several mobile phone manufactures offer GPS equipped communication devices (see Figure 5) and the trend is expected to continue increasingly in the near future. According to [5], 60 percent of WCDMA handsets will be GPS/Galileo enabled by 2010.

Figure 5. Nokia N95 with integrated A-GPS receiver.

In order to make the integration possible, the developers have been forced to design GPS receivers that can be fitted in tiny spaces at low cost in high volumes. The designed receivers have to acquire position fix and operate in harsh signal propagation environments quickly with low power consumption. These requirements and the availability of wireless connection itself have triggered a solution called Assisted GPS. Lately, the imminent introduction of the next generation GNSSs, such as Galileo, has demanded the standardisation bodies to begin modifying the wireless network specifications to support positioning methods based on these new constellations. Both Assisted GPS and Assisted GANSS concepts are presented in the following sections.

5.1 Assisted GPS

As the name reveals, Assisted GPS uses assistance data to speed up the process of acquiring the position fix especially in a weak signal environment. At the same time, it can also reduce the consumption of the receiver resources (battery power and CPU time) by delegating some of the tasks to an external entity named commonly as Assistance Server. Assistance Server has an access to a reference network of GPS receivers that are placed in ideal locations (direct line-of-sight to satellites). The reference network, used as source for the assistance data, can be maintained by a local cellular network operator or provided by an external service provider. For example, Global Locate has developed Long-Term Orbit (LTO) technique [26] where assistance data is collected by tracking the GPS constellation through Worldwide Reference Network (WWRN).

There are two possible approaches to implement A-GPS. In MS/UE assisted mode, receiver performs pseudorange measurements (utilizing assistance data provided by the Assistance Server) and sends the measurements back to the Assistance Server, which then calculates the location of the receiver. This mode is not preferable for cases, where the location is updated frequently, because the process requires significant amount of data to be transferred over the communication network. In order to reduce the amount of data transfer, MS/UE based mode can be used. In that case, the Assistance Server provides the assistance data to the receiver, which then acquires the GPS signals from the satellites and operates afterwards like an autonomous GPS receiver calculating its own location.

5.1.1 Assistance data

Depending on Assistance Server and A-GPS receiver capabilities, the assistance data may contain various elements which are listed below.

5.1.1.1 Ephemeris

In order to calculate its own 3D position, the GPS receiver needs know the locations of at least four satellites and the time of arrival of the encoded signal sent from each of the 4 satellites. Normally the locations of the satellites are acquired directly from the GPS satellites. However, downloading this satellite ephemeris from the GPS signals is time-consuming (download speed is only 50bps). In a weak signal environment (e.g. urban canyons), this data can be completely inaccessible. Since the navigation data is not location specific, it can be received by a remote receiver that has a clear line of sight to the same satellites and can be supplied to the A-GPS receiver via wireless network.

Ephemeris data is valid only for the visibility period of each detected satellite. This time is approximately 4 hours assuming that the receiver is static and the satellite is just rising above the horizon. However, ephemeris data can be loaded for a longer period of time. For example, Global Locate [7] has issued a patent, which claims the fundamental steps of generating, distributing and utilizing long term orbit (LTO) assistance data [6]. LTO assistance data (sometimes known as "extended ephemeris") allows mobile devices to have pre-calculated ephemeris for all the detected satellites.

5.1.1.2 Almanacs

Almanacs data include coarse satellite locations (simplified ephemeris). Almanacs are not precise enough for navigation but useful for speeding up the satellite search when acquiring the position fix. Almanacs are used in estimating the Doppler shifts of each satellite. The validity period of almanac data is much longer than the validity of precise ephemeris, usually weeks.

5.1.1.3 Satellite health data

In addition to location of the satellites (ephemeris, almanacs), assistance data may contain satellite health data including reports about scheduled satellite maintenance operations, outage and malfunctions.

5.1.1.4 Satellite clock errors

GPS satellites have highly accurate atomic clocks onboard. Despite the high accuracy, the drift of these clocks cause degradation of the positioning accuracy. In order to address this source of inaccuracy, information about the satellite clock errors, measured by the reference ground stations, can be included in the assistance data.

5.1.1.5 Ionospheric & tropospheric corrections

As described in sections 3.1 and 3.2, ionospheric and tropospheric corrections can be transmitted via specific communication links (e.g. VHF radio channel) or directly from satellites (e.g. EGNOS). Yet, the same information can also be included in the assistance data transmitted via cellular network.

5.1.1.6 Time and its uncertainty

The assistance data may contain time and its uncertainty. Coarse time estimate (greater than few micro seconds) can be used to restrict the search range for the relative code phases of the satellite signals after the initial signals have been acquired. If the time is precise enough (within few microseconds), it can also be used to limit the search range for absolute code phases before the initial signal has been acquired.

5.1.1.7 Initial receiver location and its uncertainty

Initial receiver location is a 3-D location with uncertainty ellipsoid. It can be estimated e.g. based on the Cell-ID method, which is one of the standardised cellular network based positioning methods in 2G and 3G networks. Initial receiver location is used to estimate satellite Doppler frequencies when acquiring the GPS signals. The location estimate does not have to be outstandingly accurate: an average error of 4 Hz in satellite Doppler frequency is introduced for every 10 km offset in position. It is recommended that the position estimate should be at least within 1000 km from the correct receiver position. If this is not the case, the signal acquisition can actually perform worse than without using the initial location estimate.

5.1.1.8 Additional time specific information

Alternatively to position, time and satellite information, the assistance data may contain approximate code phases and Doppler offsets with the corresponding uncertainties at a certain instant in time for each of the satellites in view.

5.1.2 Standardisation

Assistance data can be supplied either in control plane or in user plane. Control plane approach means that the assistance data is sent via signalling channels of cellular networks. The data is provided by an Assistance Server, which is integrated into the network infrastructure. The other option is to transfer the data via standard communication channels (e.g. GPRS). In this user plane approach, the terminal makes a secure TCP/IP connection directly with an Assistance Server. User plane solution is architecturally simpler and thus less expensive to implement and maintain. It also allows third parties to develop and host location based services without having to modify the cellular network itself. In control plane approach, the biggest advantage is that it allows operators to deploy services to subscribers either with or without data connectivity.

5.1.2.1 Control plane

The standardised control plane approach is defined both for 2G and 3G cellular networks. The basic architecture consists of a Serving Mobile Location Centre (SMLC) responsible for position determination, Mobile Positioning Centre (MPC)/Gateway Mobile Location Centre (GMLC), and location based applications. MPC/GMLC operates as a gateway for the location based applications which reside outside the cellular network. SMLC keeps track of the location information for each of the terminals and transfers information from the MPC/GMLC to the terminal and vice versa. Administrative functions such as authentication, billing, etc. are also managed by MPC/GMLC. The specifications for Radio Resource LCS Protocol (RRLP) in 2G and Radio Resource Control (RRC) in 3G are [9] and [10] respectively.

5.1.2.2 User plane

The standardised user plane approach is defined in the OMA SUPL v1.0 specification [4]. The basic idea is that the SUPL Enabled Terminal (SET) makes a secure TCP/IP connection directly with the SUPL Location Platform (SLP). The SET and the SLP exchange messages using the User Plane Location Protocol (ULP), which is encoded in ASN.1 format. The transport layer for ULP is TCP/IP, with the exception of SUPL_INIT message. SUPL_INIT is sent from SUPL Location Centre (SLC) to SET to request SET to initialize a connection to SLC. As no TCP/IP connection exists in this phase, the SUPL_INIT message is transferred to SET using either WAP Push or SMS. The port number for ULP reserved in IANA is 59910. Under the control of SLC, there can be multiple SUPL Positioning Centres (SPCs) sharing the load of interacting with SETs as shown in Figure 6. SLC may also serve external service providers or other SETs that act either as SUPL Agents or as Mobile Location Services (MLS) Clients. The communication between SLC and MLS Client/SUPL Agent is done by using Mobile Location Protocol (MLP) [54]. In The SUPL architecture is presented in more detail e.g. in [8].

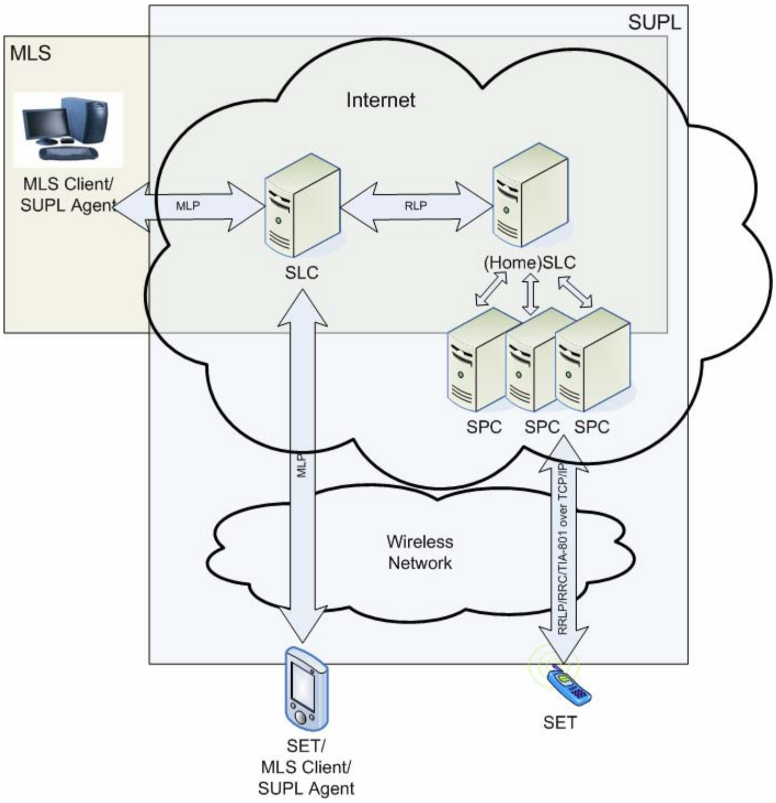

Figure 6. High level SUPL/MLS architecture [8].

SUPL v2.0 standardisation is currently underway. The specification is scheduled to be released during the year 2007. The new release will introduce many important features such as positioning WLAN SETs, Event/location-triggered location request (LR), Periodical LR, Prioritization of LRs/support for emergency LR, and SET positioning initiated by another SET [3].

5.2 Assisted Galileo and Additional Navigation Satellite Systems

Similarly to A-GPS concept, assistance data over the cellular networks will be provided to the next generation GNSSs as well. A positioning technique that utilizes one or more new satellite constellations together with assistance data over cellular or other wireless network is often called as Assisted GNSS (A-GNSS). However, in 3GPP standardisation it is named to be Assisted Galileo and Additional Navigation Satellite Systems (Assisted GANSS). The differences between assistance data for the existing GPS and the future constellations are presented in this section. The latest status of the standardisation activities (3GPP, OMA) is also covered.

5.2.1 Assistance data

The assistance data for the next generation GNSSs will be quite the same compared to the data utilized in the current A-GPS technique. The main inequalities are listed in Table 1.

Table 1. Main differences in assistance data between A-GPS and A-GNSS.

Assistance data:	Differences:
Reference time	GPS Time of Week (TOW) is not sufficient way to represent time e.g. in Galileo system. Thus, the reference time in A-GNSS data is represented as GANSS Time of Day (TOD). It can be converted into GNSS specific system time using the relations that are specified along with the reference time.
Ionospheric model	The optional ionospheric model of A-GNSS is more enhanced than the model of A-GPS: The data may contain GANSS ionosphere regional storm flags that notify about the ionospheric storms separately for five different regions.
Navigation model	The navigation model of A-GANSS may contain data for 32 satellites at most whereas the model for A-GPS can have data only for up to 16 GPS satellites. Similarly to A-GPS, A-GANSS navigation model includes satellite ephemeris, clock corrections and clock and orbit accuracy models.

5.2.2 Standardisation

The OMA SUPL specification [4] facilitates Assisted-GNSS (A-GNSS) operation but the underlying RRLP and RRC control plane protocols do not yet support it. Some modifications have already been introduced in the 2G networks but the standardisation process is not complete. In respect of 2G networks, the latest releases of the standards at issue do not yet contain any modifications related to A-GNSS.

As the modifications done by 3GPP to RRLP and RCC protocols have a direct effect on OMA SUPL V2 (planned to release in 2007), the standardisation process is likely to proceed quickly during the present year. The following section will present both the modifications that are already introduced and the recommendations for the remaining parts presented in more detail in [3].

5.2.2.1 Modifications to 2G control plane protocols

In the control plane of 2G networks, all the positioning message structures are completely linked with GPS and are fixed, so they cannot be modified. Thus, new structures must be introduced and, on the other hand, backward compatibility has to be guaranteed. Added to this, to allow location procedures based on not just Galileo, but the other future satellite constellations and hybrid usage of multiple GNSS, the new structures need to be adaptive enough to allow evolution towards new improvements. According to [3], the introduction of Galileo will cause changes to the following positioning messaging protocols: Classmark Info Type 3, Radio Resource (RR), Base Station system Application Part (BSSAP), Radio Resource LCS Protocol (RRLP) and Base Station System Mobile Application Part – LCS Extension (BSSMAP-LE). The affected specifications are enclosed in parentheses after the name of the protocol/message.

5.2.2.1.1 Classmark Info Type 3 (TS24.008)

The Classmark Info Type 3 message describes the capabilities of the mobile phone. The 'MS Positioning Method Capability' element is currently a fixed bitmap of 5 bits. It specifies which of the following positioning methods are supported by the phone: MS assisted/based E-OTD, MS assisted/based A-GPS and conventional GPS. The latest release of the standard (Release 7, March, 2007) does not yet take into account the possibility of having Galileo or other additional positioning capabilities.

According to [3], information related to additional positioning methods like Galileo has to be added in a separate bitmap. It could be a 3bit field called 'MS Galileo Positioning Method', which indicates the Galileo positioning method(s) supported by the device (MS assisted/based Galileo, conventional Galileo). This approach is generic but does not take into account the other future constellations like modernized GLONASS. Other more flexible (but not generic) solution is to create a new bigger additional element called 'MS GNSS Capability'. It would be a bitmap of 8 bits defining the GNSS supported by the phone. Half of the bits would be left undefined for future technologies.

5.2.2.1.2 RR (TS44.018 & TS24.080)

When the location supplementary service is activated, RRLP messages are encapsulated in RR messages. There is no direct impact to these messages but the registration of the mobile phone to request a location service involves 'Messages for Supplementary Services' which needs to be modified with respect to Galileo and other future GNSSs. More precisely, the affected messages are according to [3]:

- LCS Mobile Location Request (LCS MOLR) arguments (location method, GPS assistance data)
- LCS-Return Result (location method used for the location)
- Location Notification/Location Notification Argument (identifier of the location method used)
- Return result (location method type).

The latest releases of the standards in question (TS44.018 Release 7, March, 2007 and TS24.080 Release 7, September, 2006) do not yet contain the required modifications.

5.2.2.1.3 BSSAP and BSSMAP-LE (TS 48.008 & TS49.031)

The BSSAP messages (encapsulated in BSSMAP-LE messages) are exchanged between the MSC and BSC. To support Galileo and other future GNSS, 'Perform Location Request' and 'Perform Location Response' messages have been modified in BSSMAP-LE protocol. In addition to the 'Location Type' and 'GPS Assistance Data' elements, the 'Perform Location Request' message contains now two new elements named as 'GANSS Location Type' and 'GANSS Assistance Data'. Similarly, the 'Perform Location Response' message contains an additional element called GANSS Positioning Data. The new elements are described shortly in Table 2.

Table 2. New elements of the 'Perform Location Request/Response'.

Element:	Description:
GANSS Location Type	This element identifies the GANSS Location type. If the GANSS Location Type is missing, it means that all the satellite systems included in GANSS are referred.
GANSS Assistance Data	This element identifies the GANSS assistance data requested for an MS.
GANSS Positioning Data	This is a variable length information element providing positioning data associated with a successful or unsuccessful location attempt for a target MS using GANSS.

5.2.2.1.4 RRLP (TS44.031)

The changes in the RRLP include additional elements to 'Measure Positioning Request', 'Measure Position Response' and 'Assistance Data' messages. The new elements are described shortly in Table 3, Table 4, and Table 5.

Table 3. New elements of the 'Measure Positioning Request' message.

Element:	Description:
GANSS Positioning Method	This bit map indicates the satellite systems allowed by the SMLC corresponding to allowance of 'GPS' in the Positioning Methods field. Each bit is of type Boolean, where TRUE ('1') means the particular satellite system is allowed.
GANSS Carrier-Phase Measurement Request	This element does not have any information contents. If this element is present, the MS is requested to return carrier phase measurements in the GANSS Measurement Information IE.
GANSS TOD – GSM Time Association Request	This element does not have any information contents. If this element is present, the MS is requested to return GANSS TOD – GSM time association measurements. Only either GPS Timing Assistance Measurement Request Element or GANSS TOD – GSM Time Association Measurement Request should be present in Measure Position Request.

Table 4. New elements of the 'Measure Positioning Response' message.

Element:	Description:
GANSS Location Information	GANSS Location Information element provides the GANSS location estimate from the MS to the SMLC, if the MS is capable of determining its own position. Optionally, the element may contain Reference Frame element for including accurate relation between the cellular frame and GANSS Time of Day (TOD) for the serving cell if requested by the SMLC.
GANSS Measurement Information	GANSS Measurement Information element provides GANSS measurement information from the MS to the SMLC and GANSS TOD – GSM time association if requested by the SMLC. This information includes the measurements of code phase, Doppler, C/N_o and optionally accumulated carrier phase that is also called accumulated deltarange (ADR), which enable the network-based GANSS method where position is computed in the SMLC.

Table 5. New elements of the 'Assistance Data' message.

Element:	Description:
GANSS Assistance Data	GANSS Assistance Data elements are of two different types: GANSS Common Assistance Data and GANSS Generic Assistance Data. GANSS Common Assistance Data element is included at most only once and it contains Information Elements that can be used with any GNSS constellation (Reference Time & Location, Ionospheric Model). GANSS Generic Assistance data element can be included multiple times depending on the number of GNSS constellations supported in the GANSS Assistance Data. It contains information related to e.g. Time Model, DGANSS Corrections, Navigation Model, Real-Time Integrity, and UTC Model. If the field GANSS ID is missing, the data refers automatically to Galileo.
GANSS Carrier-Phase Measurement Request	This element is optional and controls if the MS should return carrier-phase measurements in GANSS Measurement Information IE to the SMLC.
GANSS TOD – GSM Time Association Request	This element is optional and controls if the MS should return GANSS TOD -– GSM Time Association Measurements to the SMLC.

In addition to the protocols presented above, the Galileo and other future GNSS will introduce major changes to the LCS test procedures (TS51.010) and AGPS performance requirements and tests (TS 25.171 and TS 34.171.). These specifications have to be updated in order to define tests and performance requirements related to the new satellite constellations and their joint usage as well.

5.2.2.2 Modifications to 3G control plane protocols

Currently, the latest releases of the 3G specifications do not support the A-GNSS concept. However, the UMTS Radio Access Network (RAN) working groups are presently finalizing the required modifications. The required changes related to each UMTS interface depicted in Figure 7 are presented in [3] and summarized in the following sections. The affected specification numbers are enclosed in parentheses after the name of the interface.

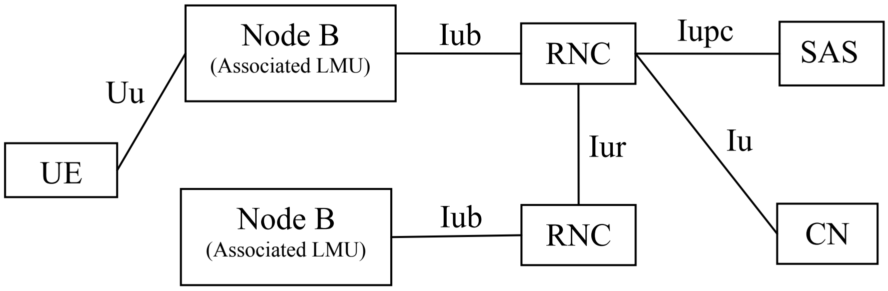

Figure 7. UTRAN interfaces.

5.2.2.2.1 Uu (TS25.331 & TS25.305)

Uu interface connects the User Equipment (UE) to the UMTS Terrestrial Radio Access Network (UTRAN). Radio Resource Control (RRC) protocol is used through this interface to transfer assistance data. The UTRAN may also send 'Measurement Control' messages to the UE, which replies with 'Measurement Report' messages to transfer measurement results back to UTRAN. The RCC data structures need to be modified to take into account several satellite constellations instead of just GPS. According to [3], this can be done by adding a parameter describing the number of constellations and utilizing a constellation identifier to map the data to a specific constellation. The UE positioning procedures and methods in specification TS25.305 should also be modified to take into account the GNSS methods and procedures.

5.2.2.2.2 Iupc (TS25.453)

The Positioning Calculation Application Part (PCAP) protocol handles the connection over the Iupc interface, which is used to allow communication between a Radio Network Controller (RNC) and a Storage Application Server (SAS). PCAP includes position estimate requests and responses as well as UE Positioning related information using mechanisms consistent with the other internal UTRAN interfaces. The Iupc interface is used for providing the RNC with UE Positioning data to be used for both point-to-point and broadcast purposes. The PCAP needs to be modified to handle assistance data and measurements related to the next generation satellite navigation systems.

5.2.2.2.3 Iur (TS25.423)

Two RNCs are connected through the Iur interface. The Iur interface is used to communicate between the UE Positioning functional entities associated with the Serving Radio Network Controller (SRNC) and other RNCs in the UTRAN. The Iur interface is also used to communicate between the SRNC and the Internal UE

Positioning Applications in the UTRAN. Similarly to Iupc, the Iur protocol needs to be modified to support new GNSS assistance data and measurements.

5.2.2.2.4 Iub (TS25.433)

A Node B is connected to the RNC through the Iub interface. The interface passes measurement requests, measurement results and requests for UE Positioning related transmissions between the UE Positioning entities associated with the Controlling Radio Network Controller (CRNC), the Node B and the associated Location Measurement Unit (LMU). New elements need to be added to the corresponding messages to be able to support A-GNSS.

5.2.2.2.5 Iu (TS25.413)

The Radio Network Subsystem (RNS) is connected to the Core Network (CN) through the Iu interface. Location Services (LCS) entities in the CN use this interface to communicate with UE Positioning entities in the UTRAN using Radio Access Network Application Part (RANAP) protocol. The messages related to location reporting, broadcasting of assistance data and assistance data requests need to be modified in order to support A-GNSS.

5.2.2.3 Modifications to OMA SUPL protocol

As mentioned earlier, the OMA SUPL protocol uses RRLP and RRC messages to deliver assistance data and pass measurement and position requests and responses. Thus, the modifications required to support A-GNSS have to be made first at 3GPP level. The higher level SUPL messages need to be modified as well. These messages are listed in Table 6.

Table 6. Required modifications to SUPL messages.

Message:	Modification:
SUPL Init	The message contains reference to the supported position techniques. Galileo and the other GNSSs have to be added to this list.
SUPL POS INIT	The message contains the bitmap corresponding to the requested A-GPS data. An additional A-GNSS element has to be added.
SUPL Response	Similarly to SUPL Init, the SUPL Response contains the positioning method to be used. This has to be modified to support various A-GNSS methods.

6. The playground

The research field of GNSS and satellite navigation is remarkably wide. Numerous organizations, associations, research institutes, companies, and universities are taking part in its research and development. To be able to get a better insight into the field, an extensive search was performed to list useful sources of information. It is needless to say that the list is not complete, since the research work is carried out all around the world. Therefore the information collected for this chapter is aimed to be only a starting point for a knowledge base to be updated and monitored regularly in the future. The knowledge base could be created in the Internet/Intranet (e.g. Twiki pages) to be able to update and distribute the information easily.

6.1 Associations, organisations, agencies and magazines

Table 7 lists associations, organisations, agencies and magazines involved in the field of satellite based navigation and positioning. Some of the introduced organizations are also involved in maintaining the existing operational systems and thus, will provide up-to-date information about the latest status of these systems. The intention of this list is to offer an extensive selection of useful links that can be used to follow the latest news in this research field.

Table 7. Associations, organizations, agencies and magazines involved in satellite based navigation and positioning.

Name:	Description:
European Space Agency (ESA)	**Background:** ESA was established in 1975 and is an inter-governmental space organization of Europe. It has currently 17 member states. **Objectives:** Concerning satellite navigation, ESA is building Galileo navigation system together with European Satellite Navigation Industries and European Union. **Tasks:** ESA is currently participating in Galileo In-Orbit Validation and developing its satellite based augmentation system EGNOS. ESA's Navigation webpage offers the latest news related to development of Galileo and EGNOS.
Galileo Joint Undertaking (GJU)	**Background:** The Galileo Joint Undertaking (GJU) has been set up by the European Commission and ESA. **Objectives:** GJU is managing the development phase of the Galileo Programme. Galileo will be Europe's own global navigation satellite system, providing highly accurate, guaranteed global positioning service under civilian control. It will be interoperable with GPS and GLONASS, the two other global satellite navigation systems. **Tasks:** The GJU is overseeing the establishment of a partnership between the public and the private sector in order to manage the Galileo Programme and mobilise the required funds. In addition, GJU has launched through ESA a first series of satellites to ensure the large-scale demonstration of the capabilities and reliability of the Galileo system (Galileo In Orbit Validation). GJU is also managing EU's 6th Framework Programme for Research and Development (FP6) Galileo related activities and responsible for managing the integration of EGNOS – the European Geostationary Navigation Overlay Service, a system that enhances the data provided by GNSSs.
GPS Exchange Website, National Aeronautics and Space Administration	**Background:** NASA is an agency of the United States federal government, responsible for the nation's public space program. NASA was established in 1958.

(NASA)	**Objectives:** Concerning satellite navigation, NASA is a vital player taking part in the modernisation process of the Global Positioning System. **Tasks:** NASA is hosting a website for GPS information exchange. It is an international information service organized by country via a clickable map display and depicts public and private sector GPS uses and their associated benefits. The idea is to illuminate the many uses of this advanced satellite based technology and to generate new concepts for the entire world to pursue.
GPS World	**Background:** GPS World, the magazine, has covered the global positioning industry since 1989. The website began providing the same coverage in 1998. **Objectives:** GPS World aims to be an information dissemination system providing the latest news in the field of global positioning, navigation and timing. **Tasks:** Despite the name, GPS World chronicles also the development of other GNSSs, augmentation systems, and issues related to satellite based navigation. GPS World is available both in electronic format (see the webpage) and in paper format.
Information Analytical Centre (IAC)	**Background:** IAC was established by Russian Federal Space Agency (Roscosmos) in 1995. **Objectives:** The objective of IAC is to operate as a tool for analysis, development and introduction of the perspective methods and technologies in the Russian coordinate and time supply. **Tasks:** Provides precise ephemeris and time determination of GLONASS and GPS. It also supports satellite navigation data archiving and distribution for the Russian and world research communities.
Inside GNSS	**Background:** Inside GNSS is a business and technology magazine for the GPS, GALILEO and GLONASS communities. **Objectives:** Inside GNSS is a business publication covering the policies, programs, engineering, and most challenging applications of GPS, Galileo, GLONASS and related technologies. **Tasks:** Inside GNSS delivers the magazine to a carefully selected international audience of 40,000 product designers, system integrators, technical managers, manufacturers and service providers as well as military, government and corporate procurement professionals.
International Committee on Global Navigation Satellite Systems (ICG)	**Background:** The ICG was established at the United Nations International Meeting for the Establishment of the International Committee on Global Navigation Satellite Systems (ICG) held in the 1st–2nd of December 2005 in Vienna, Austria. **Objectives:** ICG is an informal body for the purpose of promoting cooperation, as appropriate, on matters of mutual interest related to civil satellite-based positioning, navigation, timing, and value-added services, as well as compatibility and interoperability among the GNSS systems, while increasing their use to support sustainable development, particularly in the developing countries. **Tasks:** ICG will establish a provider's forum to enhance compatibility and interoperability among current and future global and regional space-based systems. It will also organize workshops and monitor the level of interoperability and standardization among GNSS constellations and augmentation systems.
Location	**Background:** Location is a portal on satellite navigation, positioning and timing. **Objectives:** Location portal is intended for those interested and involved in GPS related activities. It is hoped that it will foster a growing network by keeping the community up to date on many activities in this wide and varied field. **Tasks:** LOCATION magazine consists of articles related to satellite navigation, positioning and timing. The website also provides news and interviews related to these topics.
Location and Timing KTN	**Background:** The Location and Timing KTN is a managed network of more than 450 organisations (800 members) which research, develop, operate and apply location and timing technologies. It is funded by the UK Department of Trade and Industry and established in 2005. **Objectives:** The objective of Location and Timing KTN is to promote innovation in key technologies related to location and timing. **Tasks:** The task is to bring together diverse organisations and provide activities and initiatives that promote the exchange of knowledge and the stimulation of innovation in these communities. In addition, Location and Timing KTN offers information and news resources to everyone via its web forum.

Royal Institute of Navigation (RIN)	**Background:** RIN is a British society formed in 1947. **Objectives:** RIN aims to unite in one body those who are concerned with or who are interested in navigation and to further its development. **Tasks:** RIN encourages the creation and dissemination of knowledge through research, to co-ordinate information from all the disciplines involved, to provide a forum in which new ideas and new products can have the benefit of informed and professional scrutiny and to further education and communication.
Satellite Navigation Product Teams, Federal Aviation Administration (FAA)	**Background:** FAA is an agency of the United States Department of Transportation. It regulates and oversees all aspects of civil aviation in the U.S. **Objectives:** The FAA is working to overcome the deficiencies in today's air traffic infrastructure and guide the future of the United States' National Airspace System (NAS). **Tasks:** FAA is developing and maintaining two satellite based systems, the Wide Area Augmentation System (see 3.2.1) and the Local Area Augmentation System (see 3.1.3), which will provide the accuracy, availability, and integrity needed to use GPS as a primary means of navigation in aviation.
Saturn Consortium	**Background:** The consortium was formed by Chronos Technology, the National Physical Laboratory (NPL), and Bath University in 2007. **Objectives:** The objective is to understand better the local availability and integrity of GNSS transmissions. In addition, the goal is to enhance susceptibility or immunity of GNSS applications to external interference. **Tasks:** Saturn Consortium will investigate problems associated with interference, jamming, and multi-path activity affecting the integrity of GNSS applications.
The Institute of Navigation (ION) ION Proceedings ION Journals	**Background:** The Institute of Navigation is a non-profit professional society founded in 1945. Although basically a national organization, its membership is worldwide, and it is affiliated with the International Association of Institutes of Navigation. **Objectives:** ION is dedicated to the advancement of the art and science of navigation. Its goal is to serve a diverse community including those interested in air, space, marine, land navigation, and position determination. **Tasks:** ION organizes international technical meetings e.g. ION GNSS Meeting, held in September. It also publishes its quarterly journal called Navigation and sponsors five major annual awards for researchers and student awards for navigation excellence.
U.S. Coast Guard – Navigation Centre	**Background:** The Navigation Centre (NAVCEN) is the United States Coast Guard's Navigation Centre of Excellence. **Objectives:** NAVCEN operates the Navigation Information Service (NIS), the Nationwide Differential Global Positioning System (NDGPS), and LORAN. In addition, NAVCEN serves as the civilian interface for the Global Positioning System and manages other navigation-related projects. **Tasks:** The NIS disseminates navigation and maritime safety information to the public via the Internet and through a 24-7 clock in the NAVCEN Operations Centre. The Operations Centre also controls 84 NDGPS sites and 24 LORAN stations across the United States. In addition, NAVCEN serves as the civilian interface to the Department of Defence on GPS operations and management.
University NAVSTAR Consortium (UNAVCO)	**Background:** UNAVCO is a Non-profit membership-governed consortium funded through the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA). Member organizations are primarily research universities who study deformation of the Earth's crust, addressing mechanisms for large and small scale tectonic features and processes, such as earthquakes, volcanoes and plate motion. **Objectives:** UNAVCO's mission is to support and promote high-precision measurement techniques for the advancement of Earth Sciences. **Tasks:** The Scientific Working Groups of UNAVCO serve as a mechanism to involve a broad range of scientists in focusing and coordinating scientific research based on GPS technology. They serve to identify critical scientific research problems, to promote co-ordinated scientific research to address those problems, and to identify critical technical and infrastructure needs related to those research efforts.

6.2 Universities and research institutes

Table 8 lists universities and research institutes that are involved in satellite based navigation and positioning. The list is far from being complete, since there are many universities that do not have English web pages or have only outdated information about their research activities. The list aimed to be a useful source of information in searching scientific articles as well as finding partners for co-operation projects in the field of satellite navigation. Research areas that are closely related to the next generation GNSSs are highlighted.

Table 8. Universities and research institutes involved in satellite based navigation and positioning.

University/research institute:	Key research areas in the field of GNSSs:	Links:

Aerospace Controls Lab, Michigan Massachusetts Institute of Technology, Cambridge, USA	o Formation flying and carrier differential-phase GPS relative navigation
	  o Pseudolite augmented navigation for GEO communication satellite
	  o GPS estimation algorithms for precise velocity, slip and race-track position
	  o Advanced guidance algorithms for spacecraft formation flying
		Research topics
		Publications

Astronomical Institute, University of Bern, Bern, Switzerland	o Maintenance of International GPS service (IGS) analysis centre o IGS Centre for Orbit Determination in Europe (CODE) o Satellite Laser Ranging (SLR) o GPS Software Development o Modelling and Analysis	Research topics Publications
CAA Institute of Satellite Navigation, University of Leeds, Leeds, UK	o GNSS SIS evaluation, integrity and monitoring o **GNSS receiver development (also Galileo receivers)** o GNSS interference and propagation o GPS and GLONASS signal characterisation and assessment o Precise GNSS measurement campaigns	Research topics Publications More publications
Danish GPS Centre	o The mathematics of GPS o Post processing of GPS observations o **Global atmospheric water vapour profiling using GPS and Galileo satellites** o **Member of Galileo network** o 3-D monitoring of active tectonic structures o Exploitation of ground based GPS for climate and numerical weather prediction application	Research topics Publications
Department of Geodesy & Geoinformatics, Stuttgart University, Stuttgart, Germany	o Satellite geodesy including theoretical work and numerical analyses concerning accuracy and configuration analysis o Local positioning systems including development and test of algorithms and applications especially in robotics and industrial surveying	Research topics Publications
Department of Geomatic Engineering, University College, London, UK	o Positioning on the surface of the Earth and in near-Earth space o Measurement of plate tectonics and sea level	Research topics Publications

	○ Modelling of the gravity field and other reference surfaces ○ Navigation for safety critical applications and mobile devices ○ Time transfer	

Department of Spatial Information Science and Engineering, University of Maine, Orono, Maine, USA	○ Spatio-Temporal Models
	  ○ Databases for moving objects
	  ○ Location based services
	  ○ Event based models
	○ Sensor Based Systems
	○ User Interfaces and Interactions
	○ Information Integration
	○ Information Policy: Access, Security, Privacy, Intellectual Property Rights
		Research topics
		Publications

Department of Spatial Sciences, Curtin University, Perth, Australia	○ Inertial navigation system (INS), dead reckoning (DR) and GPS/GLONASS integration ○ Intelligent transportation systems (ITS) ○ Kalman filter application and algorithm development ○ Advanced least squares estimation and analysis ○ GPS applications in GIS and mapping ○ **GPS/GLONASS integration for navigation systems** ○ GPS software and algorithm development ○ High precision long baseline GPS – data processing, modelling and applications ○ Regional precise GPS orbit determination ○ Local ground deformation monitoring using integrated geodetic measurement techniques ○ GPS heighting	Research topics Publications

Electronic Navigation Institute, Tokyo, Japan	○ More efficient use of airspace and its capacity enhancement
	  ○ Satellite based augmentation systems
	  ○ **High accuracy satellite positioning using QZSS**
	  ○ Kinematic GPS improvements
	  ○ Near real-time tropospheric delay estimation
	○ Airport Capacity Enhancement
	  ○ Ground based augmentation system development
	○ Improvement of safety and efficiency with risk control and advanced technology
	  ○ Radio signal environment for aeronautical radio navigation services
	  ○ Multipath error reduction in radio positioning system
	  ○ Advanced aeronautical satellite communication system using internet technologies
		Research topics
		Publications
		More publications

Geodesy and Geodynamics Laboratory, Swiss Federal Institute of Technology, Zürich, Switzerland	○ Geodynamics including GPS based determination of crustal deformation, and seismicity
	○ Satellite geodesy and navigation
	  ○ Kinematic GPS and precise navigation
	  ○ Characteristics of GPS antenna and multipath effects
	  ○ DGPS-aided flight approaches
	○ Troposphere modelling
	  ○ GPS tomography and assimilation in numerical weather models
	  ○ GPS based path delays and 4D tropospheric
		Research topics
		Publications

	refractivity field o Ocean surface topography modelling	
Geodetic Engineering Laboratory, Swiss Federal Institute of Technology, Lausanne, Switzerland	o Mobile mapping (e.g. vehicle fleet tracking) with GPS/INS coupling and digital cameras o Laser scanning with accurate airborne mapping system that integrates laser scanner, digital imagery and navigation sensors (GPS/INS) o GPS & sports (e.g. performance analysis) o Road management (traffic control, congestion monitoring) o Pedestrian navigation (Dead reckoning based on inertial Micro-Electromechanical Systems (MEMS))	Research topics Publications
Geodetic Research Laboratory, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada	o development and assessment of GPS and GLONASS o Tropospheric and ionospheric propagation delay modelling o Time and frequency synchronisation on low-earth-orbiting (LEO) spacecraft o Differential systems used in conducting helicopter approaches to offshore structures o High-precision RTK GPS positioning	Research topics Publications
GPS Laboratory, Ohio State University, Columbus, USA	o GPS algorithms and methods o RTK GPS in multi-station environment o LEO and GPS orbit determination o Space weather monitoring with GPS o GPS/INS integration for direct sensor georeferencing o Sensor integration and mobile mapping o Airborne and land-based mapping supported by GPS/INS o Outdoor and indoor use of GPS pseudolites o Application of GPS in location based services	Research topics Publications
GPS Research Laboratory, Stanford University, Palo Alto, California, USA	o Galileo, new signals, and signal monitoring o Controlled Reception Pattern Antenna (CRPA), resistance of interference and jamming o Position Navigation Time (PNT) based Encryption (Geoencryption) In addition, the GPS Research Laboratory works with the Federal Aviation Administration, U.S. Navy, U.S. Air Force, Arinc, NASA and U.S. Coast Guard **to pioneer systems that augment the Global Positioning System (GPS) and Galileo**.	Research topics Publications
Imperial College Engineering Geomatics Group, Imperial College, London, UK	o Reliable map-matching algorithms for land transport applications o Robust navigation algorithms for aircraft precision approach and landing using GNSS o Determination of carrier phase observation ambiguity applying EGNOS message for precise point positioning o Seamless Positioning in All Conditions and Environments o Robust statistical framework for monitoring the integrity of GNSS, and preparing the marketplace for integrity-based services	Research topics Publications
Inertial Navigation and GPS Lab, University of California, Berkeley, USA	o Data fusion o Inertial navigation o Differential GPS	Research topics Publications
Institute for Astronomical and Physical Geodesy, Faculty of	o Utilizing GPS to model: o Accurate rotation of the Earth	Research topics Publications

Civil and Geodetic Engineering, Munich Technical University, Munich, Germany	o Atmospheric parameters for meteorology and climatology o Phase centre correction for GPS receiver and satellite antennas o Comparisons of homogeneously reprocessed GPS and Very Long Baseline Interferometer (VLBI) long time-series of troposphere zenith delays and gradients o Real Time Kinematic GPS o GPS heighting	
Institute of Engineering Surveying & Space Geodesy, The University of Nottingham, Nottingham UK	o Seamless positioning in all conditions and environments using GPS and inertial sensors o **GPS-based positioning to localize underground pipes and cables (also by simulating the possibilities to use Galileo and modernized GPS)** o Tropospheric water vapour effects on nationwide RTK GNSS o **The science and technology behind Galileo** o **Preliminary research on 'Assisted GNSS for LBS in China'**	Research projects Publications
International Institute of Air & Space Law, Faculty of Law, Leiden University, Leiden, Netherlands	o Space law research including laws related to GNSS and Galileo o Legal aspects of offering service guarantees in the context of LBS o Liability for global navigation satellite services	Research topics Publications
Laboratory of Geodesy & Geomatics Engineering, Department of Mineral Resources Engineering, Technical University of Crete, Chania, Greece	o High precision satellite navigation and geodetic positioning o Establishment of permanent GPS array station in the Technical University of Crete o Monitoring of the tectonic and geodynamic motion of the earth's crust, etc. o Satellite altimetry o Sea level changes o Data quality control	Research topics Publications
Laboratory of Geodesy, Department of Civil Engineering, Division of Geotechnical Engineering, University of Thessaloniki, Thessaloniki, Greece	o Monitoring the deformation of technical works and ground landslides o Control of geometrical quality of structures and industrial products o Establishment and operation of a Continuous Reference GPS station in Thessaloniki o Applications of Global Positioning System in Geodesy, Geodynamics and Vehicle control and navigation o The influence of the atmosphere on radio wave propagation o Surveying monuments and archaeological sites	Research topics Publications
Mathematical Geodesy and Positioning, Department of Earth Observation and Space Systems of the Faculty of Aerospace Engineering, Delft University of Technology, Delft, Netherlands	o Active GPS Reference System (AGRS.NL) consisting of an array of permanent satellite tracking stations evenly distributed over the Netherlands o Virtual Reference Station (VRS) concept used in Real Time Kinematic (RTK) applications o GPS meteorology where the GPS signal delay caused by water vapour in troposphere is used in weather predictions o The International GLONASS Experiment (IGEX) focusing on global calibration of GLONASS and GPS and their integrated use o **EGNOS System Test Bed (ESTB) – monitor-station** o **Study of the new signal introduced in the next**	Research topics Publications

	generation GNSSs to estimate their impact on ambiguity resolution o Research on the Least-squares Ambiguity Decorrelation Adjustment (LAMBDA) method, which is the numerical mechanisation for computing the integer least-squares ambiguities o Monitoring and modelling land subsidence by using GPS receivers o Baseline length and the ionosphere o Baseline height and the troposphere o GNSS array-based, geometry-free ambiguity resolution o GNSS variance-component estimation o GPS integer ambiguity resolution	
Navigation and Guidance Laboratory, Illinois Institute of Technology, Chicago, USA	o LAAS o Leonard (Autonomous Ground Vehicle) o Shipboard Relative GPS (SRGPS) Navigation System o GPS/INS implementation	Research topics Publications
Navigation Group, Institute of Digital and Computer Systems, University of Tampere, Tampere, Finland	o Augmentation of GNSS using sensors o Pedestrian dead reckoning mechanization o Robust integration algorithms o Real-time processing of sensor signals o Enhancements to system reliability by signal integrity monitoring o Receiver autonomous integrity monitoring: fault detection, isolation, and exclusion o Statistical reliability testing, and internal and external reliability o Probabilistic methods for signal integrity reasoning o Detection of environment characteristics o Integrity monitoring using sensor information	Research topics Publications

Personal Positioning Algorithms Research Group, Tampere University of Technology, Finland	o Hybrid positioning (satellite based systems (such as GPS), terrestrial radio systems (such as cellular networks), and on-board sensors)
	o Nonlinear filtering
	    o Bayesian inference
	    o sequential Monte Carlo methods
	    o (extended) Kalman filters
	    o numerical integration methods
		Research topics
		Publications

Satellite Navigation and Positioning Lab, School of Surveying and Spatial Information Systems, Sydney, Australia	o GPS interference studies o **Designing next generation GNSS receivers using the software approach** o Ground deformation monitoring using GPS o Creating software development kits for testing A-GPS performance, indirect signal tracking, ultra-tight GPS/INS integration, pseudolite tracking, and high-sensitivity carrier phase-tracking (for surveying applications) o Pseudolite augmentation of GPS o Field Programmable Gate Arrays (FPGA) studies in GPS receiver design	Research topics Publications
Satellite-Based Positioning and Navigation Group, University of Calgary, Calgary, Canada	o **Determining the accuracy and reliability advantages of combining GPS and Galileo** o **Investigating the effect of a new satellite system on urban users** o Real-time processing of GNSS data for safety critical applications	Research topics Publications

	○ Multiple reference station GPS RTK precise positioning
	○ Urban canyon and indoor location
	  ○ RF propagation models
	  ○ Integration of high sensitivity GPS, ground based RF and self-contained sensors	

Space and Geophysics Laboratory, University of Texas, Austin, USA	○ GPS receiver design ○ Monitoring the quality of the GPS signal ○ Precise GPS differential positioning ○ Remote sensing and specification of the ionosphere ○ Gravity field monitoring	Research topics Publications
Space Research Centre, University of Texas, Austin, USA	○ GPS navigation and attitude control of spacecraft ○ Relative navigation ○ Satellite formations ○ Precise orbit determination ○ Multisensor integration	Research topics Publications

6.3 Companies

Table 9 lists companies that are involved in satellite navigation and positioning. The focus is on next generation GNSS developers, especially on European companies that are participating in Galileo Programme funded by ESA, EC and GJU.

Table 9. Companies involved in satellite based navigation and positioning.

Company	Description:
Aena	**Focus areas:** • Galileo service provider and operation manager **Recent projects/achievements:** • Aena has participated in several Galileo project including GalileoSat phase B2, GALA, GEMINUS, INTEG, Galilei, Saga and GEM. • Aena is currently participating in the GIANT and GARMIS projects.
Andrew Corporation	**Focus areas:** • A-GPS assistance server • Hybrid positioning (cellular network based methods, WiMAX, and satellite based positioning) **Recent projects/achievements:** • Geometrix MLC
BlueSky Positioning Ltd	**Focus areas:** • Location based services specifically designed for GSM and 3G mobile phones. **Recent projects/achievements:** • BlueSky Positioning's product, A-GPS SIM, is the world's first Assisted-GPS module for SIM cards. Together with GSM or 3G phones, it forms a complete network assisted GPS receiver capable of locating the handset quickly and accurately.
Deimos Space SI	**Focus areas:** • Mission and data systems • Real-time systems • Space software systems **Recent projects/achievements:** • Galileo Programme: constellation mission control system assessment

EADS Astrium	**Focus areas:** • Satellite systems, payloads and equipment for Galileo **Recent projects/achievements:** • Galileo Programme: ESN Industries is supplying one of the two Galileo system test satellites, GIOVE-B, built by Astrium. In January 2005 ESA awarded ESN Industries the contract for the Galileo in-orbit validation (IOV) phase to test the new satellite navigation system under real mission conditions. The agreement provides for the construction of the first four constellation satellites and part of the ground infrastructure for Galileo to 2009, and then the testing of this partial system.
Finmeccanica	**Focus areas:** • Design, development and production of navigation satellites **Recent projects/achievements:** • Finmeccanica is one of the contractors for Galileo's space segment.
HISPASAT	**Focus areas:** • Infrastructure development (Galileo Control Segment (GCS)) • Standardisation of regulations • Promotion satellite navigation R+D activities **Recent projects/achievements:** • HISPASAT will operate the Galileo Control Segment (GCS)
Inmarsat Plc	**Focus areas:** • Satellite based telecommunications services • Performance monitoring and operations security **Recent projects/achievements:** • Inmarsat has the overall management leadership of the Galileo Operations Company (OpCo), the arm of the business that will look after global network operations, including performance monitoring and operations security.
LogicaCMG	**Focus areas:** • Software engineering • Security • Development of mission critical scientific algorithms **Recent projects/achievements:** • LogicaCMG has developed the unit that verifies the EGNOS message before and after transmission. The LogicaCMG integrity check set (LICS) is the most critical element of EGNOS since it ensures that the information being broadcast is absolutely reliable. • LogicaCMG is participating in the development of the key security features for Galileo Programme.
Nottingham Scientific Ltd	**Focus areas:** • Development of intellectual property for applications related to improved positioning techniques • Mission critical software development for space programmes • Provision of GNSS best practice consultancy • Monitoring and analysis of the performance of GNSS • Development of prototype systems for specialist applications **Recent projects/achievements:** • Algorithm prototyping for the orbit determination and time synchronization of Galileo • Galileo Phase C0, Support to Ground Mission Segment • Galileo System Test Bed Version 1 E-OSPF, generation of the Navigation and Signal In Space Accuracy (SISA) products
Skysoft Portugal	**Focus areas:** • Software technology for navigation terminals • Development of simulation and design aiding tools for software and hardware receivers

	Recent projects/achievements: • Terminal user segment of Galileo Programme
TeleOp	**Focus areas:** • Operation and maintenance of Galileo **Recent projects/achievements:** • TeleOp is one of the shareholders in the Galileo concessionaire and will be responsible for important aspects of operating and maintaining the system.
Thales Alenia Space	**Focus areas:** • Satellite on-board equipment • Ground equipment **Recent projects/achievements:** • EGNOS • MT-SAT 2 – Air navigation and telecommunications space system for Japan • Galileo Programme: Thales Alenia Space is participating in the development of GSTB and GIOVE A+B

6.4 Relevant projects

The Table 10 summarizes relevant ongoing and ended projects pertaining to the next generation Global Satellite Navigation Systems. Most of the presented projects are part of the Galileo Joint Undertaking and funded by European Commission.

Table 10. Relevant projects related to next generation GNSSs.

Project:	Description:
AGILE	**Equals to:** "Application of Galileo in the LBS Environment" **Objectives:** Agile will to consolidate the position of European industry in the emerging LBS domain. It will also lay the foundations that will enable Galileo to be smoothly and successfully adopted by existing and future LBS applications **Tasks:** AGILE will develop pre-commercial EGNOS-based applications and define innovative methods to improve the inherent availability and accuracy of LBS, considering the various usage scenarios of the specified applications and current or near future wireless protocols. This hybridisation process will bridge the gap between high accuracy GNSS-based technologies and high availability mobile network positioning. **Duration:** 2005–2007
BEAR	**Equals to:** "Bear ethology around Romania" **Objectives:** BEAR aims to develop improved tracking in difficult GNSS environments. As a secondary aim, it will investigate improved animal management techniques for bears in the Transylvanian mountains. **Tasks:** BEAR will develop algorithms to combine satellite tracking with local terrain models and maps to improve positioning performance. **Duration:** 2006–2007
GIANT	**Equals to:** "GNSS introduction in the aviation sector" **Objectives:** GIANT aims to support the introduction of EGNOS and Galileo services in the aviation market while demonstrating to the responsible authorities that the required safety levels are maintained. **Tasks:** GIANT will identify all the necessary steps for the introduction and intensive use of EGNOS/Galileo in the aviation sector in Europe. It will also evaluate and analyse all the potential operational and economic benefits in comparison with the current scenario. In addition, it will demonstrate operational benefits to airspace users. **Duration:** 2005–2007

GIROADS	**Equals to:** "GNSS introduction in the road sector" **Objectives:** Agile aggregates the road and GNSS communities' proposals to facilitate the technical and commercial introduction of Europe's satellite navigation programme to the road transport sector. **Tasks:** AGILE will individually analyze the key applications that have the potential to become enablers of road transport policy in Europe. Based on this analysis, AGILE will determine the user requirements, assess the existing regulatory framework and build a realistic market study that can serve as a reference to the sector. **Duration:** 2005–2007
GRAIL	**Equals to:** "GNSS introduction in the rail sector" **Objectives:** GRAIL aims to achieve a common specification (agreed by users and industry) for the GNSS subsystem for the safety-critical applications of European Rail Traffic Management System (ERTMS)/ European Train Control System (ETCS). **Tasks:** GRAIL will develop and test a prototype of the GNSS subsystem for the safety-critical applications of ERTMS/ETCS. The prototype will be tested in a real line and in a lab environment. **Duration:** 2005–2007
HARMLESS	**Equals to:** "Humanitarian aid, emergency management and law enforcement GNSS applications" **Objectives:** The main objective is to research and promote the use of the European navigation satellite systems Galileo and EGNOS in the areas of emergency management, humanitarian aid and law enforcement. **Tasks:** HARMLESS will analyze a myriad of applications, such as the coordinated management of emergency equipment deployed in disaster areas, humanitarian aid logistic support, vehicles localization, offenders' control, suspects' tracking, valued goods supervision, or the collection of juridical evidences based on localization and synchronization. HARMLESS will research, demonstrate and promote these applications while involving technology experts, end-user communities and European institutions. **Duration:** 2006–2007
ISHTAR	**Equals to:** "Industrial stimuli for the harmonisation of European research in the area of location based services" **Objectives:** The objective is to identify and report on knowledge and expertise gaps particularly in terms of technological interoperability in the field of LBS at European level. **Tasks:** ISHTAR will contribute to the harmonisation of LBS standardisation efforts. It will also derive a pan-European map of expertise in the field of Location Based Services and relevant technologies and propose a five-year R&D roadmap for future R&D activities in the field. **Duration:** 2005–2006
LIAISON	**Equals to:** "Location based services for the enhancement of working environment" **Objectives:** LIAISON will consolidate the objectives for LBS in working environment. It will define the architecture of an end-to-end solution for LBS targeting the mobile workers in ubiquitous manner (indoor and outdoor). **Tasks:** LIAISON will perform advanced research & development activities into LBS to enhance the performances of the future solutions and enable new functionality. It will also carry out standardisation and regulatory activities for effective consolidation of the LIAISON solution and promote the system via dissemination and training. **Duration:** 2004–2007
MARUSE	**Equals to:** "GNSS introduction in the maritime sector" **Objectives:** The objective of the MARUSE project is to bring together Small Medium Enterprises (SME's), maritime GNSS industry, other GNSS industry and key service providers and users within maritime and inland waterways with the aim to introduce EGNOS and Galileo in the maritime domain. **Tasks:** MARUSE encompasses technical development activities (Maritime Galileo pseudolites, Galileo/GNSS receiver prototype capable of tracking GSTB-V2 signal and Galileo pseudolites, maritime user terminal, maritime local element, integrated navigation test bed). In addition, it will focus on market analysis, business modelling, legislation & regulations, interaction with other standardisation activities and technical

	studies. **Duration:** 2005–2007
MTRADE	**Equals to:** "Humanitarian aid, emergency management and law enforcement GNSS applications" **Objectives:** MTRADE's objective is to explore and promote GNSS (EGNOS / Galileo) use in the freight multimodal transport market. **Tasks:** M-TRADE has developed an end-to-end solution that combines GNSS (EGNOS) with RFID and GPRS commercial-off-the-shelf components, demonstrated it in real-life operations, and evaluated its introduction in customs and border control applications. **Duration:** 2006–2007
PROGENY	**Equals to:** "Provision of Galileo expertise, networking and support for international initiatives" **Objectives:** PROGENY aims to support both innovation and international initiatives around the Galileo Programme. **Tasks:** PROGENY will establish a platform for technical co-ordination of GNSS knowledge and expertise in the enlarged Europe and with different regions worldwide. In addition, it will promote cooperation by organizing events. **Duration:** 2005–2008
SPACE	**Equals to:** "Seamless positioning in all conditions and environments" **Objectives:** The primary aim of SPACE is to undertake the basic research needed to build a prototype GNSS-based positioning system that can deliver cm-level accuracy positioning everywhere and any time. **Tasks:** SPACE will investigate multipath modelling and mitigation, quality control and assessment, measurement modelling and integration, and GNSS sensor design. **Duration:** 2004–2007
Swirls	**Equals to:** Swirls is not an acronym but refers to Galileo Professional Rx Development **Objectives:** The target of the project is to build the prototype of a Galileo/GPS receiver for the professional market. **Tasks:** Designing and implementing a Galileo/GPS receiver prototype. **Duration:** 2005–2007

7. Concluding remarks

The introduction of new satellite constellations and augmentation systems, more advanced signal schemes, and the A-GPS/A-GNSS concept is bringing satellite based positioning closer to its ultimate goal: getting instant, reliable, accurate position at any time and at any place with reasonable cost. For service providers and receiver manufactures, this will provide new business opportunities. On the other hand, the diversity of emerging technologies may also create uncertainty. The wide spectrum of available system and signals raises questions such as: Should the service/receiver rely on only one GNNS or should it support multiple satellite constellations? Which signals will be interoperable? In addition, the political armwrestling behind the scenes is making it even harder to predict, which GNSSs and augmentation systems will be operational and when.

7.1 Increased performance expectations

Along with the improvements in satellite based position, new application areas are emerging increasing the demands for the seamless localization. The receivers are expected to work accurately in all environments including indoor spaces and narrow street canyons. According to [49], the expectations of GNSS navigation performance may soon conflict with system limitations.

A good example of a bit overvalued and misunderstood technology has been the A-GPS: The abbreviation is often interpreted as Anywhere GPS instead of its real meaning, Assisted GPS. As mentioned in [63], the claims that A-GPS systems can deliver fixes “anywhere, anytime” are overstated. The sensitivity of A-GPS receiver required by cell phone standards is not enough to enable GPS positioning indoors. In addition, a dynamic environment e.g. a street canyon with pedestrian and automobile traffic can be even more challenging for A-GPS receivers due to the multipath propagation of the satellite signals [63]. However, by combining the usage of assistance data and a high-sensitivity (HS) GPS receiver, a positioning fix can even be achieved (after several second) inside a shopping mall more than 100 meters from the nearest exit and maintained the fix with reasonably good accuracy (median error of 17 metres) [68].

On the other hand, the integration of GNSS and wireless communication devices will also provide new opportunities to augment satellite navigation with terrestrial radio network based positioning techniques. For instance, Wireless Local Area Network (WLAN) presents already now an existing infrastructure for indoor positioning, as it has become increasingly popular in offices and public areas with an increasing number of mobile terminals supporting it. Other short-range wireless techniques that could be used in positioning include Bluetooth, Zigbee, mobile WiMAX and Ultra Wide Band (UWB) [69]. Even TV signals are being successfully tested to enhance the performance of A-GPS [70].

The hybrid usage of several GNSSs increases the number of satellites visible for the receiver. In addition, the geometry of the satellites (DOP) is also likely to be better when utilizing signals transmitted from multiple systems. As a result, the positioning accuracy will be better than with only one GNSS as it is shown e.g. in Figure 8. Besides utilizing multiple constellations, a joint use of multiple signals having different carrier frequencies can be exploited in mitigating e.g. the positioning error caused by ionospheric delays [73]. A similar improvement can also be achieved by utilizing differential corrections provided by e.g. a satellite based augmentation system such as EGNOS (see Figure 8). A comprehensive study of performance benefits from multiple satellite systems and multiple carrier signals using GPS and virtual Galileo measurements is presented in [72].

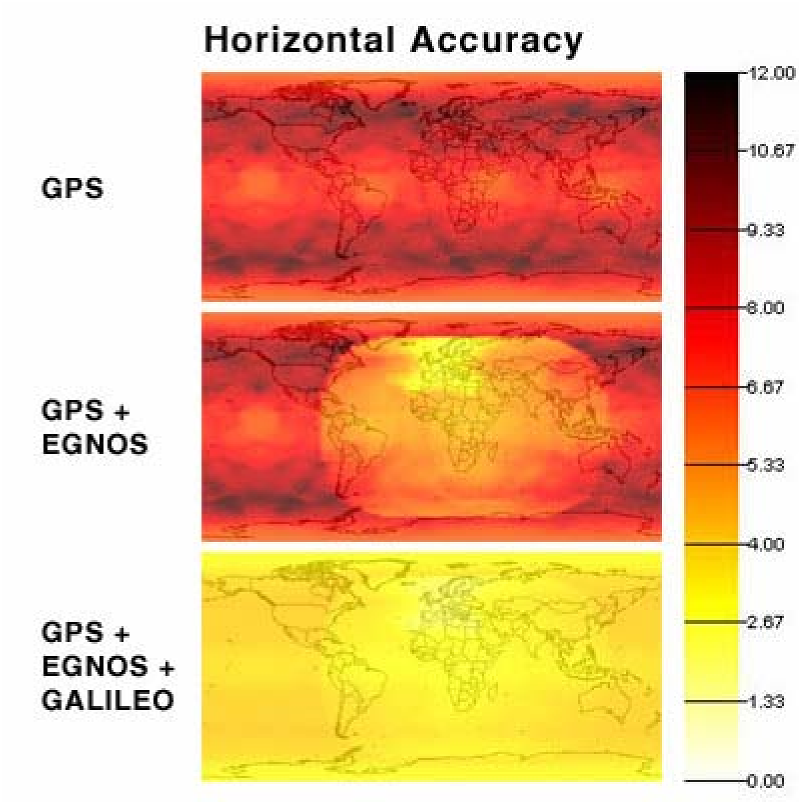

Figure 8. Simulation of horizontal positioning accuracy (RMS) in meters with GPS, EGNOS and Galileo [61].

Accuracy and availability are not the only performance characteristics that are being increasingly requested from the navigation services. Many safety-critical applications rely on the satellite based positioning. The developers of Galileo have taken this into account by planning to implement a range of service levels (see section 2.3.1) offering several degrees of integrity and service guarantees. In addition, the augmentation systems like the EGNOS (see section 3.2.2) provide fault detection and integrity information for GNSS services. Furthermore, military and government-authorised groups such as the police demand protection against jamming and spoofing. This is taken into consideration when developing e.g. the new GPS M-Code [71].

In addition to the increased performance requirements, GNSS receivers are expected to consume less power and to be able to fitted in tiny spaces e.g. inside the covering of a mobile phone. These claims have forced the receiver manufacturer to develop some interesting innovations such as the world's first Assisted GPS module fitted in a mobile phone's SIM card [28].

7.2 Interoperability and political aspects

As mentioned in the previous section, interoperability of various satellite systems will benefit the users by improving the performance of the positioning service. More satellites in the sky increase the positioning availability, accuracy and also that a given level of accuracy is achieved sooner. More signals also mean that the service is less vulnerable to interference of jamming of one frequency [74].

According to [55], the possible signal combinations of the existing and planned satellite systems are:

- GPS and QZSS: L1, L2 and L5
- GLONASS: L1, L2 and L3
- Galileo: L1, E5 and E6
- GPS, QZSS and GLONASS: L1, and L2
- GPS, QZSS and Galileo: L1, L5/E5 (only suitable combination for safety-of-life applications).

International Committee on Global Navigation Satellite Systems (ICG) was established in 2005 to promote the cooperation between the developers of GNSSs. The objective for ICG is to increase collaboration on matters of mutual interest related to civil satellite-based positioning, navigation, timing, and value-added services, as well as compatibility and interoperability among the GNSS systems [75].

Despite the recent efforts on establishing global cooperation through ICG, the evolution of GNSSs may be in many occasions a direct consequence of the national policies that intend to promote economic and political interests [56]. For example, Galileo was planned to be the first satellite positioning and navigation systems specifically designed for civil purposes [53]. However, one of the driving forces behind the EU's decision to implement its own GNSS was the concern regarding reliance on third party systems such as the GPS and the GLONASS [56]. Eventually, last year EU's Transport Commissioner Jacques Barrot proposed that Galileo would be used also for military purposes in order to recover rising development costs of the system [76].

Some concrete steps towards interoperability have been taken. For instance, in 2004, United States and EU signed landmark agreement on GPS-Galileo cooperation. According to the agreement, both parties will recognize importance of compatibility and interoperability for all parties. They also agreed to spectrally separate signals for military and civilian services and to implement a common, open, civil signal on both Galileo and GPS III [77].

In 2006, United States and Russian Federation agreed to sign a Joint Statement to promote the efforts on the interoperability and compatibility issues between GPS and GLONASS [78]. However, Russia has not yet confirmed whether GLONASS satellites will start using CDMA signals to ease the dual use of the two systems [33].

According to [19], India is in the process of backing out of a pre-agreement to sign on as a Galileo partner due to the fact that China is also planning to participate in the project. At the same time, India continues its connection with traditional ally Russia via investment in GLONASS [19] but has also signed a joint statement together with US to cooperate in the use of GPS and space-based positioning, navigation and timing systems and applications [20].

China remains to be the biggest questions mark in terms of cooperation. Even though China has shown interest towards participation in Galileo Programme, Galileo officials have privately expressed a concern that the expansion of Chinese own satellite system Beidou could undermine the Galileo business case [79].

7.3 Predicted schedule for the GNSS developments

The scheduled events related to the modernisation of GPS and GLONASS as well as the estimated milestones for Galileo, Compass, IRNSS and QZSS are depicted in Figure 9. As it has been seen many times before, the scheduled events are more than likely to be delayed. Among other things, poor weather conditions may delay the launch of a new satellite into its orbit, unexpected technical problems may occur like in [65] and political/economical disagreements may slow down the development work [59]. Thus, the presented timetable is only suggestive and subject to change.

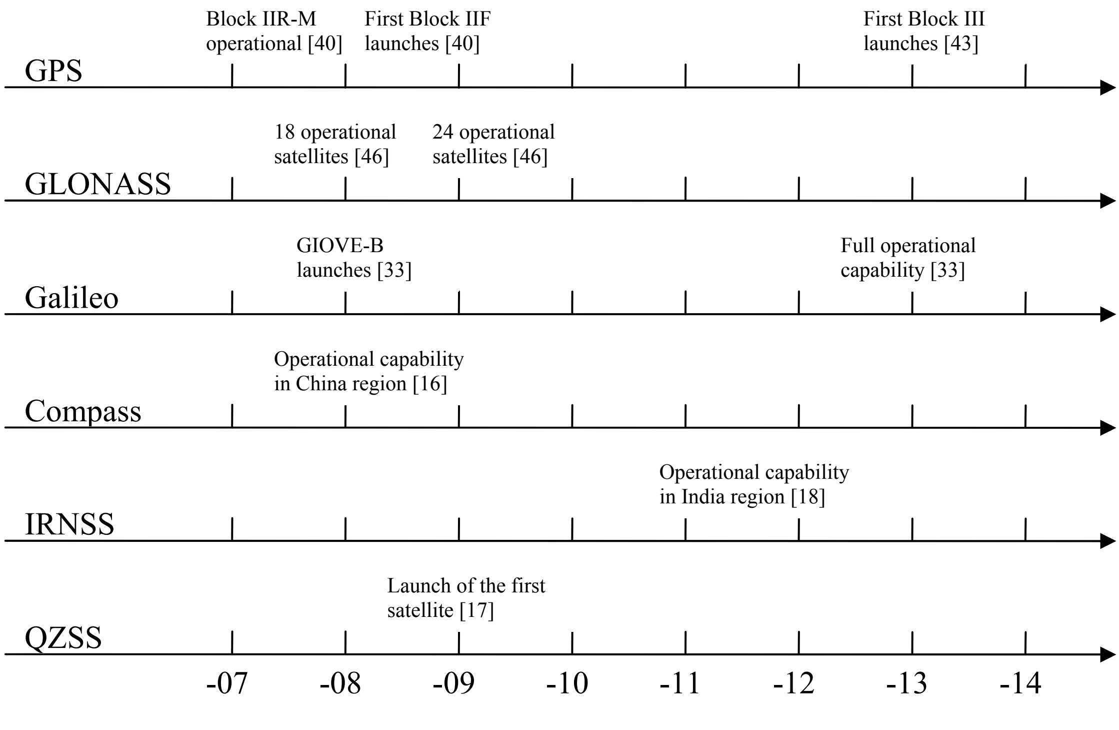

Figure 9. Estimated schedule for the GNSS developments.

References

[1] The NASA Global Differential GPS, http://www.gdgps.net/. Web site accessed 4 April 2007.

[2] S. Raman, L. Garin, "Performance Evaluation of Global Differential GPS (GDGPS) for Single Frequency C/A Code Receivers," in *Proc. ION GNSS 2005*, Long Beach, CA, USA, September 2005.

[3] "Galileo LBS standardisation activities recommendations", ISHTAR-WP2-AAS-D24, ISHTAR Consortium, 2006, http://www.eu-ishtar.net/ISHTAR_WP2_D2.4.final_PDF.zip. Web site accessed 4 April 2007.

[4] OMA Secure User Plane Location V 1.0 Candidate Enabler, http://www.openmobilealliance.org/release_program/supl_v1_0.html. Web site accessed 4 April 2007.

[5] Berg Insight: 60 percent of WCDMA handsets will be GPS/Galileo enabled by 2010, http://www.tekrati.com/research/News.asp?id=8206. Web site accessed 12 April 2007.

[6] J. Romano, "Global Locate Issued Patents for GPS, Long Term Orbit Technology (LTO™)," in *Global Locate's Press Release*, October 2005, http://www.globallocate.com/PRESS/Press_Releases/GL_Issued_GPS_LTO_Patents.htm. Web site accessed 24 April 2007.

[7] Global Locate, http://www.globallocate.com/. Web site accessed 24 April 2007.

[8] "Overview of MOTIVE concept applications", MOTIVE-WP2-D21, MOTIVE Consortium, 2006, http://www.cn.ntua.gr/ist-motive/docs/wp2-d2-1_v1-1.pdf. Web site accessed 4 April 2007.

[9] Location Services (LCS); Mobile Station (MS) – Serving Mobile Location Centre (SMLC) Radio Resource LCS Protocol (RRLP), Release 7, http://www.3gpp.org/ftp/Specs/html-info/44031.htm. Web site accessed 8 May 2007.

[10] Radio Resource Control (RRC); Protocol specification, Release 7, http://www.3gpp.org/ftp/Specs/html-info/25331.htm. Web site accessed 8 May 2007.

[11] DGPS reference station network of Finnish Maritime Administration, http://www.fma.fi/e/services/radionavigation/. Web site accessed 8 May 2007.

[12] Fact Sheets – LAAS, http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/laas/index.cfm. Web site accessed 8 May 2007.

[13] EGNOS for Professionals, http://www.esa.int/navigation/egnos-pro. Web site accessed 16 May 2007.

[14] OmniSTAR, The Global Positioning System, http://www.omnistar.com.au/index.html. Web site accessed 16 May 2007.

[15] "New Beidou Satellite," in *GPS World*, April 2007.

[16] "And Beidou Makes Four," in *GPS World*, November 2006.

[17] "JAXA Backs First QZSS Sat," in *GPS World*, May 2006.

[18] "India Aloft," in *GPS World*, July 2006.

[19] "India Retreats from Galileo," in *GPS World*, October 2006.

[20] United States – India Joint Statement, "Cooperation in the Use of GPS and Space-Based Positioning, Navigation and Timing Systems and Applications", http://pnt.gov/public/docs/2007-india-statement.shtml. Web site accessed 17 May 2007.

[21] The StarFire Network, http://www.navcomtech.com/StarFire/. Web site accessed 17 May 2007.

[22] VueStar – Global Aerial Survey Navigation System, http://www.navcomtech.com/Products/GPS/vuestar.cfm. Web site accessed 17 May 2007.

[23] Fact Sheets – Wide Area Augmentation System, http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/. Web site accessed 17 May 2007.

[24] A. El-Rabbany, *Introduction to GPS: The Global Positioning System*, Artech House, 2002.

[25] "End of test bed marks a new era for EGNOS," in *ESA Navigation News*, July 2006, http://www.esa.int/esaNA/SEMNG7XAIPE_egnos_2.html. Web site accessed 22 May 2007.

[26] D. Lundgren, F. van Diggelen, "Assistance When There's No Assistance," in *GPS World*, October 2005.

[27] R. B. Langley, "The Mathematics of GPS," in *GPS World*, Vol. 2, No. 7, July/August 1991, pp. 45–50.

[28] Bluesky Positioning's product: the world's first Assisted-GPS module for SIM cards, http://www.blueskypositioning.com/products.htm. Web site accessed 24 May 2007.

[29] M. Prasad, "Location is everything," in *Location*, March–April, 2006.

[30] A. Das, "GPS Augmentation System," in *Location*, Jan–Feb, 2007.

[31] J. Ventura-Traveset, F. Toran, J.P. Lam, P. Michel, “The European EGNOS Project: Mission, Program and System Description,” in *Location*, Jan–Web, 2007.

[32] M. Kishimoto, “Quasi-Zenith Satellite System: Status and Design,” in *Location*, Jan–Feb, 2007.

[33] “GNSS Updates,” in *ION Newsletter*, Vol. 16, No. 4, Winter 2006–2007.

[34] A. El-Rabbany, “Mining Positioning,” in *Proc. Smart Systems for Mineral Resources Workshop*, Toronto, Ontario, February 14, 2001.

[35] M. O. Kanli, “Limitations of Pseudolite Systems Using Off-The-Shelf GPS Receivers,” in *Journal of Global Positioning Systems*, 2004, Vol. 3, No. 1–2, pp. 154–166.

[36] S. Cobb, M. O'Connor, “Pseudolites: Enhancing GPS with Ground-Based Transmitters,” in *GPS World*, Vol. 9, No. 3, March 1998, pp. 55–60.

[37] “Sneak Preview L5”, in *GPS World*, April, 2007.

[38] J. B. Fernandes, “GPS/Galileo Signal Structure and Interoperability,” in *Location*, 2006.

[39] GPS Modernisation Fact Sheet, http://pnt.gov/public/docs/2006-01-modernization.pdf. Web site accessed 27 May 2007.

[40] “The Year of IIR-M: Five May Rise in 2007,” in *GPS World*, November, 2007.

[41] “M-Code Tested,” in *GPS World*, October, 2007.

[42] A. Dempster, “Correlators for L2C – Some Considerations,” in *Inside GNSS*, September, 2006.

[43] D. A. Turner, “Space-Based PNT Modernisation Update,” in *Presentation to the Munich Satellite Navigation Summit*, February 21–23, 2006.

[44] GLONASS – Summary, Space and Tech Database, http://www.spaceandtech.com/spacedata/constellations/glonass_consum.shtml. Web site accessed 29 May 2007.

[45] E. Gakstatter, “GLONASS – The Comeback Kid” in *GPS World*, June, 2006.

[46] S. Revnivykh, “GLONASS: Policy, Status and Modernisation Plan,” in *Presentation to the Munich Satellite Navigation Summit*, February 21–23, 2006.

[47] R. B. Langley, “The GPS Receiver: An Introduction,” in *GPS World*, Vol. 2, No. 1, January, 1991, pp. 50–53.

[48] H. Sairo, *Error Detection in Personal Satellite Navigation*, Doctoral Thesis, Tampere University of Technology, 2006.

[49] I. G. Petrovski, “Everywhere, without waiting,” in *GPS World*, October, 2006

[50] S.U. Qaisar, J. Wu, A. Dempster, “Loud and Clear: Receiving the new GPS L2C and Galileo signals”, in *UNSW SNAP Snippets*,

http://www.gmat.unsw.edu.au/snap/new/pdf/NewSignalsFeb07.pdf. Web site accessed 29 May 2007.

[51] GPS constellation status for 28.05.07 under the analysis of the almanac accepted in IAC, http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:30:8092565305074578765::NO. Web site accessed 29 May 2007.

[52] GLONASS constellation status for 28.05.07 under the analysis of the almanac and accepted in IANC, http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:20:8092565305074578765::NO. Web site accessed 29 May 2007.

[53] S. Muriel, *Galileo - European Programme for Global Navigation Services*, ESA Publications, 2005, http://esamultimedia.esa.int/docs/galileo/GalileoE3web_copy.pdf. Web site accessed 29 May 2007.

[54] Mobile Location Service v1.0, Open Mobile Alliance, http://www.openmobilealliance.org/release_program/mls_v1_0.html. Web site accessed 29 May 2007.

[55] C. Rizos, M.B. Higgins, S. Hewitson, "New Global Navigation Satellite System developments and their impact on survey service providers and surveyors," in *Proc. International Federation of Surveyors*, October 2005.

[56] M.S. Khan, "Political and economic dimensions of Global Navigation Satellite System (GNSS)," in *Proc. IEEE Aerospace Conference 2001*, Vol. 3, March, 2001, pp. 1271–1276.

[57] K. M. Miller, "A Review of GLONASS," in *Proc Hydrographic Journal*, 2000.

[58] G. W. Hein, J. Godet, J.-L. Issler, J.-C. Martin, R. Lucas-Rodriguez, T. Pratt, "The Galileo Frequency Structure and Signal Design," in Proc. of *ION GPS 2001*, 2001.

[59] "Galileo Sparring Leads to No Decision; Clock Running," in *GPS World*, March, 2007.

[60] "Galileo Lurches On; EU Sole Funder," in *GPS World*, May, 2007.

[61] "Galileo System Test Bed Version 1 experimentation is now complete," in *ESA Navigation News*, http://www.esa.int/esaNA/SEM6KYP3K3E_index_0.html. Web site accessed 30 May 2007.

[62] J. Paffett, "GIOVE-A – The First Galileo Satellite In Space," in *Presentation to the Munich Satellite Navigation Summit*, February 21–23, 2006.

[63] C. Carver, "Myths and Realities of Anywhere GPS," in *GPS World*, September, 2005.

[64] “Galileo Industries Told to Put House in Order,” in *GPS World*, January, 2007.

[65] “Second Galileo test satellite launch delayed,” in *GPS World*, September, 2007.

[66] Galileo Joint Undertaking, http://www.galileoju.com. Web site accessed 30 May 2007.

[67] “GLONASS Drawing Boards,” in *GPS World*, May, 2007.

[68] F. van Diggelen, “Global Locate Indoor GPS Chipset & Services,” in *Proc. ION GPS 2001*, 2001.

[69] P. Kemppi, Y. Li, *Indoor Positioning Survey*, Research Report, T1 Daimon project, VTT, 2006.

[70] M. Martone, J. Metzler, “Prime Time Positioning,” in *GPS World*, September, 2005.

[71] B. C. Barker, et al., *Overview of the GPS M Code Signal*, Technical Paper, MITRE Corporation, 2000, http://www.mitre.org/work/tech_papers/tech_papers_00/betz_overview/betz_overview.pdf. Web site accessed 30 May 2007.

[72] Y. Feng, et al., “Exploring Performance Benefits from Multiple Satellite Systems and Multiple Carrier Signals Using GPS and Virtual Galileo Measurements,” in *Proc. IGNSS Symposium 2006*, Surfers Paradise, Australia, 17–21 July, 2006.

[73] J. Kim, S. Cho, J. Ko, “L1/L2 dual-band CMOS GPS receiver,” in *Proc 30th European Solid-State Circuits Conference*, September, 2004, pp. 87–90.

[74] C. Rizos, “New GNSS developments and their impact on the geospatial industry,” in *GIS Development Asia-Pacific*, June, 2006, pp. 34–36.

[75] Work plan of the International Committee on Global Navigation Satellite Systems, http://www.unoosa.org/pdf/icg/2006/ICG_WP_NOV2006E.pdf. Web site accessed 30 May 2007.

[76] “Galileo Shows Military Face,” in *GPS World*, October, 2006.

[77] R. Braibanti, “GNSS International Cooperation,” in *Presentation to the Munich Satellite Navigation Summit*, February 21–23, 2006.

[78] United States – Russian Federation Joint Statement, http://www.state.gov/r/pa/prs/ps/2004/39748.htm. Web site accessed 30 May 2007.

[79] “China Wants One of Its Very Own,” in *GPS World*, November, 2006.

Appendix A: Glossary

Acronym:	Explanation:
3GPP	3rd Generation Partnership Project
CDMA	Code Division Multiple Access
CN	Core Network
CRNC	Controlling Radio Network Controller
CS	(Galileo) Commercial Service
DNSS	Defence Navigation Satellite System
DOT	(The United States) Department of Transportation
EC	European Commission
EGNOS	European Geostationary Navigation Overlay Service
ERTMS	European Rail Traffic Management System
ESTB	EGNOS System Test Bed
ETCS	European Train Control System
EU	European Union
FAA	Federal Administration of Aviation
FDMA	Frequency Division Multiple Access
FPGA	Field Programmable Gate Array
GANSS	Galileo and Additional Navigation Satellite Systems
GCS	Galileo Control Segment
GEO	Geostationary Earth Orbit
GJU	Galileo Joint Undertaking
GMLC	Gateway Mobile Location Centre
GPS	Global Positioning System
GSA	(European) GNSS Supervisory Authority
GSTB-V1	Galileo System Test Bed Version 1
GUS	Ground Uplink Station
IGS	International GPS Service
IOC	Initial Operational Capability
ION	Institute of Navigation
ISRO	Indian Space Research Organization
JPALS	Joint Precision Approach and Landing System
L1-SAIF	L1-Sub meter class Augmentation with Integrity Function
LAAS	Local Area Augmentation System
LCS	LoCation Services
LDGPS	Local Differential GPS
LMU	Location Measurement Unit
LTO	Long-Term Orbit
MCC	Mission Control Centre
MEMS	Micro-Electromechanical Systems
MEO	Medium Earth Orbit
MLP	Mobile Location Protocol
MLS	Mobile Location Services
MPC	Mobile Positioning Centre
MSAS	MTSAT Satellite Based Augmentation System
MTSAT	Multi-Functional Transport Satellite
NAS	United States' National Airspace System
NASA	National Aeronautics and Space Administration (USA)

NAVCEN	U.S. Coast Guard Navigation Centre
NAVSTAR	Navigation Signal Timing and Ranging System
NDGPS	Nationwide Differential Global Positioning System
NIS	Navigation Information Service
NLES	Navigation Land Earth Station
Node B	A base station in UTRAN
NSF	National Science Foundation (USA)
OMA	Open Mobile Alliance
OpCo	(Galileo) Operations Company
OS	(Galileo) Open Service
PCAP	Positioning Calculation Application Part
PPP	Public-private partnership
PRS	(Galileo) Public Regulated Service
PTS	Precision Timing Station
QZSS	Quasi-Zenith Satellite System
RANAP	Radio Access Network Application Part
RIMS	Ranging and Integrity Monitoring Stations
RMS	Receiving Monitor Stations
RNS	Radio Network Subsystem
RTK	Real Time Kinematic
SAR	(Galileo) Search And Rescue Service
SAS	Storage Application Server
SET	SUPL Enabled Terminal
SIS	Signal in Space
SLC	SUPL Location Centre
SME	Small Medium Enterprises
SMLC	Serving Mobile Location Centre
SoL	(Galileo) Safety-of-Life Service
SPC	SUPL Positioning Centre
SUPL	Secure User Plane Location
TAI	International Atomic Time
TCP/IP	Transmission Control Protocol/Internet Protocol
TTFF	Time To First Fix
UE	User Equipment
UNAVCO	University NAVSTAR Consortium
UPL	User Plane Location
UTC	Coordinated Universal Time
UTRAN	UMTS Terrestrial Radio Access Network
UWB	Ultra Wide Band
VBS	Virtual Base Station
WAAS	Wide Area Augmentation System
WLAN	Wireless Local Area Network
WMS	Wide-area Master Station
WRS	Wide-area Reference Station
WWRN	Worldwide Reference Network

Series title, number and report code of publication

VTT Research Notes 2408
VTT-TIED-2408

Author(s)
Kemppi, Paul

Title

Next generation satellite navigation systems

Abstract

The report gives a brief introduction to the existing and planned global satellite navigation and augmentation systems. It addresses their current status and future modernisation / development plans in addition to their basic architecture. The report also presents the idea behind pseudolites and the challenges related to them. Furthermore, the convergence of global satellite navigation systems and wireless communication devices is covered by explaining the concepts of A-GPS and A-GNSS. The two architectural approaches to implement A-GPS are discussed as well as the modifications required to the cellular network specifications introduced by next generation GNSSs. Information sources related to satellite navigation and positioning including universities, research institutes, organizations, agencies, magazines and relevant projects are also collected to this document in order to create a knowledge base of the research field. Finally, issues that affect the evolution of satellite based positioning are being discussed.

ISBN
978-951-38-6961-8 (URL: http://www.vtt.fi/publications/index.jsp)

Series title and ISSN
VTT Tiedotteita – Research Notes
1455-0865 (URL: http://www.vtt.fi/publications/index.jsp)

Project number
15683

Date
September 2007

Language
English

Pages
61 p. + app. 2 p.

Name of project

Commissioned by

Keywords
satellite navigation systems, global positioning systems, augmentation systems, pseudolites, A-GPS, A-GNSS, system architecture, cellular networks, GNSS, mobile wireless communication

Publisher
VTT Technical Research Centre of Finland
P.O.Box 1000, FI-02044 VTT, Finland
Phone internat. +358 20 722 4404
Fax +358 20 722 4374

Satellite based positioning and timing services are already used in many sectors of transport, security, surveillance, industry, research, and leisure. In the future, this trend will accelerate along with the introduction of new global navigation satellite systems (GNSS). This report presents the existing and planned global satellite navigation and augmentation systems. It addresses their current status and future modernisation / development plans in addition to their basic architecture. The report also presents the idea behind pseudolites and the challenges related to them. Furthermore, the convergence of global satellite navigation systems and wireless communication devices is covered by explaining the concepts of A-GPS and A-GNSS. A list of universities, research institutes, organizations, agencies, magazines and relevant projects is also collected to this report in order to create a knowledge base of the research work related to satellite navigation, positioning and timing.

VTT
PL 1000
02044 VTT
Puh. 020 722 4404
Faksi 020 722 4374

VTT
PB 1000
02044 VTT
Tel. 020 722 4404
Fax 020 722 4374

VTT
P.O. Box 1000
FI-02044 VTT, Finland
Phone internat. + 358 20 722 4404
Fax + 358 20 722 4374

ISBN 978-951-38-6961-8 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1455-0865 (URL: http://www.vtt.fi/publications/index.jsp)