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Global navigation satellite systems

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Abstract

Global positioning systems first became available for private use in 1995. Since the introduction of NAVSTAR-GPS (Navigation System with Time and Ranging–Global Positioning System) and GLONASS (Globaluaya Navigatsionnaya Sputnikovaya Sistema, Global Navigation Satellite System), such systems have quickly become indispensable in a wide range of applications. Above all, GPS is used today by a large user community. Artificial augmentations can be used to improve the performance of the systems in terms of accuracy, availability and integrity. In space-based augmentations, differential correction data, integrity information and additional ranging signals are transmitted from geostationary satellites. In ground-based augmentations, a reference station (based on a geo-referenced position) compares the position solution (calculated by the SatNav System) with the real coordinates. In that case, the correction data is transmitted by a telemetric system to roving receivers near the reference station. Both augmentation techniques are based on the generic satellite navigation systems GPS or GLONASS, and are dependent on the availability of the source system. To overcome the dependency of the civil European user community upon foreign military systems, an initiative to build up an autonomous European Satellite Navigation System with an own-space segment was initiated. Since 1999, the realisation of this project has been on the way, and the employment of the new system, named Galileo, is currently expected in 2008. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

In recent years, the situation of positioning and navigation has changed dramatically. Engineering advances in satellite technologies have yielded two navigation

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systems, the NAVSTAR GPS (Navigation System with Time and Ranging–Global Positioning System) developed and maintained by the US Department of Defence and the US Department of Transportation, and the Russian Global Navigation Satellite System (GLONASS, Globaluaya Navigatsionnaya Sputnikovaya Sistema). Although both are national military systems, they are available for use by the international private and commercial communities. In Europe and other areas, concern was voiced about dependence on a foreign military system and plans for a civilian global navigation satellite system (GNSS) were put in place. Plans for the system are divided into two phases. The GNSS-1 is essentially an overlay for the existing systems and still relies on them. The second phase, GNSS-2, will be completely autonomous with a separate space segment.

The dramatic drop in equipment prices over the past 10 years, from approximately 20 000 Euro for a civilian receiver to about 100 Euro for the least expensive hand-held receivers today, have lead to an enormous growth in the number of GPS users. New applications emerged; for example, car navigation systems, fleet management, aircraft approach and landing, bridge deformation monitoring, offshore drilling research, and the navigation of agricultural field machinery. These multiple applications increased the need for improved accuracy, availability, and integrity in the systems. Differential GNSS (DGNSS) is one possible solution for these advanced user requirements. Correctional data are emitted from a reference system at a known position and sent to receivers near the system. The horizontal accuracy of GPS can be improved from 100 m with selective availability (SA) down to a few meters with differential GPS (DGPS). It is even possible to achieve centimetre accuracy with high-precision receivers working with carrier phase tracking techniques.

Satellite navigation technology became of interest for agricultural applications in recent years. First experiments with automatic position detection for agricultural vehicles, supported by DGPS, were conducted and names like “precision farming” were coined. DGPS applications with accuracy of some metres are used for precision farming. High-level accuracy of several centimetres is necessary for machine guidance applications. In the meantime, some manufacturers offer real-time kinematic receivers with an accuracy of 1 cm (horizontal) and 3 cm (vertical) with an update rate of 1 Hz, or 2 cm and 5 cm (rate, 5 Hz). A system for machine guidance will fulfil the accuracy requirements for precision farming but not vice versa. The measurement of the attitude of a vehicle with accuracy of up to 0.1° is possible with multiple antenna arrangements. Such accuracy is needed for autonomous guidance (Bell, 1999) to measure and compensate vehicle movements caused by rough terrain and slopes. Another task for satellite navigation in the future will be the measurement of true ground speed of agricultural vehicles. At the moment, the GPS is unable to measure low velocity; for this reason, radar and wheel sensors are used to measure speed. Taking into account the anticipated satellite navigation technology developments for the near future, it seems that the implementation of modern navigation equipment will increase in the future. Many publications exist on the topic of satellite navigation in agriculture (for example, Auernhammer, 1994).

The development of a new satellite-based navigation system has started and will have a great impact on the agricultural sector, because the users will become independent from foreign military systems. In the long term, it is not acceptable to base the navigation applications for industry, agriculture or the private sector on systems that can be degraded or switched off without warning. This is one of the main reasons for building a civilian-operated satellite navigation system.

2. Basic principles of GNSS

Since many publications deal with the basic principles of a satellite navigation system, this section will just summarise the basic facts. The main principle behind a satellite navigation system is the creation of a trilateration from any point on the earth's surface to the satellites in view. The distance to the satellites is measured by the time the radio signal needs to reach the receiver. Because a radio signal travels with the speed of light, highly precise clocks are used. The satellites contain atomic clocks, and the receivers advanced quartz clocks. The distance to the satellite can be calculated by multiplying the travel time by the speed of light (approximately 300 000 km/s). The exact location of the satellite in space is a prerequisite for this procedure. This is possible because the orbits are very stable and predictable. The satellites are observed and controlled by ground stations, which put the spatial information into the signal. These are the so-called "ephemeris data" (orbit of one satellite) and "almanac data" (relation between all of the satellites). Additionally, information on the satellite clocks is transmitted.

In principle, three satellites must be available to determine a three-dimensional position. All points, which have the same distance to one satellite, form a spherical surface with the satellite in the centre. Three spherical surfaces intersect in two points. One point can be disregarded, because its position is located too far from the earth. A fourth signal is necessary to eliminate the time difference between the satellite's atomic clocks and the receivers' quartz clocks. This technique allows the use of inexpensive clocks in user equipment. After all, four satellites are necessary to determine a three-dimensional position. Another satellite is needed for integrity monitoring (quality control and identification of satellite malfunction). One more additional satellite is needed to identify the deficient satellite. The probability of receiving four or more GPS satellites with good geometry, quantified by a position dilution of precision (PDOP) of less than six and an elevation higher than 5° is about 99%. This is, however, a 24-h global average, and not a guarantee for the availability at a special place and time on Earth. The main influences on accuracy are:

- the geometric position of the satellites (PDOP);
- clock errors of the satellites;
- ephemeris errors;
- tropospheric and ionospheric conditions;
- multipath effects;
- inaccuracies of the receiver;

- GPS: artificial deterioration of clock and ephemeris data for civil users by the US Department of Defence (SA).

After this short introduction on the basics of satellite navigation, we will take a more detailed look at the two operable systems, GPS and GLONASS. Further current information can be obtained at the mentioned Internet addresses.

2.1. GPS (US NAVSTAR Global Positioning System)

NAVSTAR GPS is the most used satellite navigation system today. The name GPS is often used as a collective term for satellite navigation systems in general. Within this article, GPS refers strictly to the US NAVSTAR GPS, and the term global navigation satellite systems (GNSS) is used for satellite navigation.

The operational constellation of the GPS space segment consists of 24 satellites. The orbital period is 11 h 58min. The satellites are distributed on six orbits, equally spaced (60° apart), and inclined at about 55° with respect to the equatorial plane. This constellation provides the user with between five and eight satellites visible from any point on earth.

The control segment consists of a system of tracking stations located around the world. The master control facility is located at Falcon Air Force Base in Colorado. The monitor stations measure signals from the space vehicles (SV) which are incorporated into orbital models for each satellite. The models compute orbital data (ephemeris) and satellite clock corrections for each satellite. The master control station uploads ephemeris and clock data to the space vehicles. The satellites then send subsets of the orbital ephemeris data to GPS receivers through radio signals.

The GPS user segment consists of the GPS receivers and the user community. GPS receivers convert the signal in space into position, velocity and time estimates. Four satellites are required to compute the four dimensions of X, Y, Z (position) and time. GPS receivers are used for navigation, positioning, time dissemination, and other applications. The number of receivers that can be used is not limited, because they act in a passive manner.

Three-dimensional navigation is the primary function of GPS. Precise positioning is possible using GPS receivers at reference locations providing correction data for remote receivers. Surveying, geodetic control, and plate tectonic studies are examples. Time and frequency dissemination, based on the precise clocks on board the space vehicles and controlled by the monitor stations, is another use for GPS. Astronomical observatories, telecommunications facilities and laboratory standards can be set to time signals or to accurate and control frequencies by special purpose GPS receivers. Research projects have used GPS signals to measure atmospheric parameters like water vapour coefficients.

The SVs transmit two microwave carrier signals, one at 1575.42 MHz (L1) and the other at 1227.70 MHz (L2). The Course/Acquisition Code (C/A Code), which is available for private users, is broadcast at L1. This service is called that standard positioning service (SPS). The Precise Code (P-Code) for military or authorised users is broadcast on both L1 and L2. This service is called the precise positioning service.

The accuracy of the SPS is artificially degraded by SA, which is an operational mode, designed to deny hostile forces the tactical advantage of GPS positioning. The clock and the ephemeris data are falsified by the maintainer of the system. SA is the most important factor of all sources of error.

Despite these negative factors, the following accuracy can be achieved by GPS without additional means (Parkinson and Spilker, 1996):

- horizontal accuracy: 95%, 100 m; 99.99%, 300 m;
- vertical accuracy: 95%, 150 m; 99.99%, 450 m;
- time accuracy, 340 ns.

2.2. GLONASS (Russian Global Navigation Satellite System)

The Russian Global Navigation Satellite System (GLONASS), being deployed by the Russian Federation, has much in common with the US GPS in terms of the satellite constellation, orbits, and signal structure. Both systems are owned and operated by their respective defence departments, and offer global, and continuous position-fixing capabilities. Both transmit spread spectrum signals at two frequencies in the L-band (1.2 and 1.6 GHz), and have pledged to make a partial set of signals available for civil use without any user fees for the next 10 years or more. The 24 GLONASS satellites are deployed in three orbital planes. All GLONASS satellites transmit a similar code but at different frequencies.

Like GPS, GLONASS offers two levels of service. The Channel of Standard Accuracy (CSA), available to all civil users, shall provide horizontal position accuracy of 60 m with 99.7% probability, and vertical position accuracy of 75 m with 99.7% probability. The Channel of High Accuracy (CHA) shall be available only to the authorised users.

In January 1996, for the first time, the system had a full constellation of 24 working satellites. The year 1996 was also important for user equipment as new GLONASS receivers were introduced to the market. In July 1999, the GLONASS constellation consisted of 15 operable satellites.

One of the basic differences between GPS and GLONASS is the type of geographic reference systems in which the coordinates are delivered. The GPS data output-format is the World Geodetic System 1984 (WGS84), whereas the GLONASS data output-format is the PZ-90 system (Russian, Parameters of Earth 1990). Another difference is the time system. GPS works in UTC (Universal Co-ordinated Time, an atomic clock time scale co-ordinated by the Bureau International de l'Heure in Paris) and USNO time (US time standard kept by the US Naval Observatory), whereas GLONASS uses the UTC in Moscow time. One of the most significant differences between GPS and GLONASS are the signal structure and signal handling, because the GPS satellites share the same frequencies but differ in individual codes, and GLONASS satellites share the same code but differ in frequencies.

Nevertheless, it is possible to combine the two systems and improve accuracy and, especially, the availability of satellite signals. Not only GLONASS, but also GLONASS/GPS combined receivers are available on the market. Fig. 1 shows the differences between GPS and GLONASS (Zarraoa et al., 1997).

Parameter	GPS	GLONASS
Number of satellites	21 + 3 spares	21 + 3 spares
Number of orbital planes	6	3
Orbital inclination	55.0°	64.8°
Orbit altitude	20 180 km	19 100 km
Orbit period	11 h 58 min	11 h 16 min
Ground track repeat	1 sidereal day	8 sidereal days
Geodetic system	WGS 84	PZ 90
System time corrections relative to the universal co-ordinated time (UTC)	UTC (USNO)	UTC (SU)
Satellite signal division method	Code division	Frequency division
Frequency L1	1575.42 ± 1.0 MHz	1602+ n x 0.5625MHz ± 0.5 MHz (n=1,2,...,24)
Frequency L2	1227.60 ± 1.0 MHz	1246+ n x 0.4375MHz ± 0.5 MHz (n=1,2,...,24)
Number of code elements	1023	511
Code rate	C/A = 1.023 MHz P = 10.230 MHz	C/A = 0.511 MHz P = 5.110 MHz

Fig. 1. Differences GPS/GLONASS.

3. GNSS augmentation systems

For some applications, including agricultural tasks, the accuracy, availability and integrity of the stand-alone GPS system cannot meet the required performance. To improve the system, local and regional DGPS reference stations, and additional ranging facilities and information about the health status of the satellites could be established. This chapter will deal with some of the most important local and regional augmentation systems. However, it has to be kept in mind that all of the augmentation systems are based on GPS or GLONASS, and are thus dependent on foreign military forces with the consequences mentioned in Section 1.

3.1. Local Area Augmentation System (LAAS)

In general terms, a Local Area Augmentation System consists of a reference station and mobile user receivers. It can be established in any part of the world. Further information concerning the principles of DGPS are given in Section 5.1.

The LAAS broadcasts GPS correction data to an aircraft in sight of the corresponding ground reference system. Like the US wide aera augmentation systems (WAAS), the primary use for the system is avionics (especially CAT I/II/III[1]). LAAS specifications are worked out by the FAA (Federal Aviation Administration, a part of the US Department of Transportation). It is still uncertain whether or not the system will become a full-scale, federally funded

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[1] Precision approaches are divided into three categories.
CAT I: lateral accuracy, ± 10.5 m; vertical accuracy, ± 1.1 m.
CAT II: lateral accuracy, ± 7.5 m; vertical accuracy, ± 1.1 m.
CAT III: lateral accuracy, ± 3.0 m; vertical accuracy, ± 0.6 m.

development project. The FAA maintains that the LAAS CAT II/III precision approaches will be available to public users by 2005. Frequencies being considered for the LAAS use are in VHF, L-band (the same frequency as GPS and GLONASS) and C-band.

3.2. Wide Area Augmentation Systems (WAAS)

Another technique to augment GPS is to use a geostationary satellite to provide:

- Integrity information;
- Differential correction data;
- Additional ranging signal.

One example is the US WAAS, which is primarily installed for aviation purposes, but will enable many other users to improve their GPS measurements.

A network of 24 wide area reference stations receives and processes satellite data. The computation of differential corrections, integrity determination, calculation of residual errors and ionospheric information takes place at the three Wide Area Master Stations. Two Ground Earth Stations transmit this information to transponders on-board the INMARSAT-3 (International Maritime Satellite Organisation) geostationary satellites, linking it down to the user receivers. WAAS operates as an overlay on the GPS L1 signal and shares the 1559–1616 MHz frequency band.

The area of coverage is defined as the air space up to 100 000 feet over the 48 contiguous American states, Hawaii, Puerto Rico and Alaska (excluding the area west of 160° W and positions outside of the broadcast area of the geostationary satellites). The service is limited to the United States territory. No augmentation for the Latin American region is available due to the absence of ground stations. Central America could be integrated into the system with the establishment of a few ground stations. The Initial Operational Capability (IOC) will arrive in September 2000.

3.3. EGNOS European Geostationary Navigation Overlay Service

EGNOS is a space-based augmentation system with the same functions as those described in the preceding section. EGNOS, also known as GNSS-1, is based on GPS, GLONASS and INMARSAT-3 satellites and covers a region including Europe, Africa, the Middle East, some Asian countries, and even parts of South America. EGNOS provides a network of ground stations, additional ranging signals, correctional and integrity data, and communication links broadcast by the INMARSAT-3 satellites.

The two INMARSAT satellites used for EGNOS are positioned above the Indian Ocean at 64° E (launched in April 1996) and over the Atlantic Ocean at 15.5° W (launched in August 1996). They operate from a geostationary orbit 36 000 km above the Equator. The lease for the transponders is for 5 years with a possible 5-year renewal. EGNOS will provide three navigation services: ranging, integrity monitoring, and wide area differential corrections. The ranging augmentation

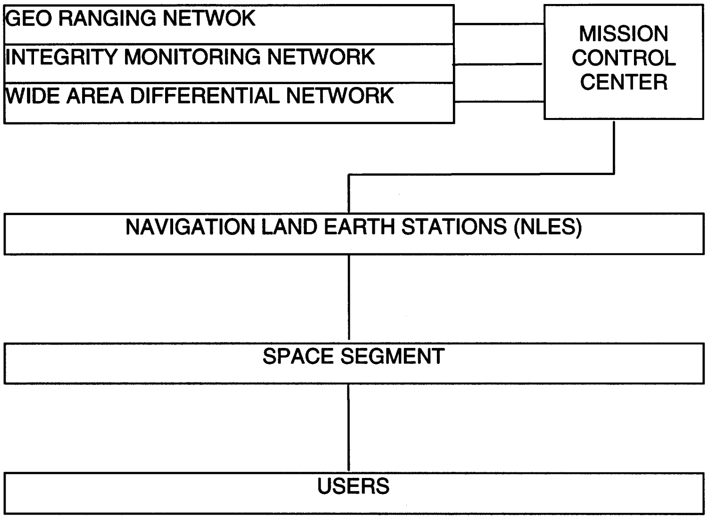


Fig. 2. EGNOS system architecture.

means that INMARSAT satellites broadcast GPS-like signals so that the user has two additional satellite signals available. The ground segment consists of reference stations, a mission control centre and two navigation uplink stations. Fig. 2 shows the system architecture of EGNOS.

EGNOS transmits test signals in 1999. Advanced operational capability should be achieved by 2003. The system will be compatible with the US WAAS.

3.4. MSAS Japanese MTSAT-based satellite augmentation system (MSAS)

The Japanese MTSAT (Multi-functional Transport Satellite)-based satellite augmentation system is a space-based augmentation system comparable with WAAS and EGNOS. Like other augmentation systems, it will consist of ranging stations, ground monitor stations, master control stations and a geostationary Space segment. It will be compatible to WAAS and other Satellite-Based Augmentation Systems (SBAS). The system will be managed and operated by the Japanese Civil Aviation Bureau (JCAB).

The launch of the first MTSAT is scheduled in 1999. It will be a geostationary satellite located 36 000 km above the Equator at a longitude of 140° E and will cover most of the Asia/Pacific air space. The MTSAT will provide users with:

- GPS-like signals (ranging function);
- GPS health conditions obtained by ground monitoring stations (integrity function);
- ranging errors (differential function).

The data will be exchanged by the feeder link between the satellite and the ground stations in the Ku-band (12/14 GHz) and the Ka-band (20/30 GHz), and the service link between satellite and user in the L-band (1.5/1.6 GHz).

Each ground station can cover a minimum circular radius of 500 km. In Japan, the six stations Sapporo, Tokyo, Fukuoka, Naha, Kobe, and Hitachi-Ota provide the integrity and differential information. In other Asian/Pacific states, additional stations are planned and will be linked to the master control station in Japan.

After the launch of MTSAT-1 in September 1999, the first operational phase will continue through the end of 2003. The second operational phase will begin with the launch of MTSAT-2 in 2004.

4. Differential GNSS accuracy

Differential data correction was developed to improve the accuracy of the GPS, and is known as differential GPS (DGPS). Differential correction data can also be used to augment other GNSS. In this context, the collective term DGNSS is used. This technique will also be available for centimetre accuracy in future navigation systems for machine guidance. In the following section, principles will be explained and some examples will be discussed.

4.1. DGNSS types and principles

The augmentation with local DGNSS correction data can be provided by public institutions or private companies. The transmission of the correctional data can be realised with either terrestrial radio signals, mobile communication systems or satellites. DGNSS service fees could be collected either as one-time payments (included in the price of the receiver), monthly/annual user fees, or fees based on the amount of data received by the user. To avoid large administration costs, the one-time user fee is probably the best approach for the mass market. For high end users, another option could be chosen.

Local area DGNSS and regional area DGNSS function with one reference station, whereas wide area DGNSS is based on a network of reference stations. The following methods are used to correct the “stand alone” positioning error:

- Correction based on inclined distance measurements. Systematic errors are included in the calculations. The error to each satellite within the scope of the reference station will be calculated and transmitted to the user, who can then choose the best possible constellation of satellites for his purposes.
- Correction based on raw data. The most accurate method, but the reference station and user receiver must be compatible and a high data rate is required. Practical for only a few local special applications but meets demands for high accuracy.

4.2. Reference stations (examples from different countries)

4.2.1. SAPOS Germany

The users of the Global Positioning System in Germany have the opportunity to use SAPOS (SAtellitenPOSitionierungsdienst der deutschen Landesvermessung, Satellite Positioning Service of the German Topographical Survey Administration). SAPOS is maintained by the AdV (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland, Working Group of the Survey Administrations of the Federal Republic of Germany), an association of federal surveying authorities and divisions of various ministries, including the Ministries of Transport, Defence and the Interior.

In May 1995, the AdV agreed to build up a DGPS service to cover German territory, providing an infrastructure for public domains but also for private applications. Ultimately, the system will comprise about 200 reference stations, each covering an area of 40–70 km.

Four different performance levels will be offered (Hankemeier, 1997):

- EPSEchtzeit Positionierungs Service (Real Time Positioning Service);
- HEPSHochpräziser Echtzeit Positionierungs Service (Highly Precise Real Time Positioning Service);
- GPPSGeodätischer Präziser Positionierungs Service (Geodetic Precise Positioning Service);
- GHPSGeodätischer Hochpräziser Positionierungs Service (Geodetic Highly Precise Positioning Service).

The characteristics of the four service levels are shown in tabular form in Fig. 3. Every level of accuracy is capable of fulfilling the requirements for precision farming and HEPS can even meet the demands of machine guidance.

To use the EPS service with an accuracy of 1–3 m, any code-tracking GPS receiver with a DGPS and RTCM interface is sufficient. For the other services, more complex carrier phase tracking receivers are required. Appropriate navigational equipment is currently available from four different producers. Coordinate-output is based on the European Terrestrial Reference System 1989 (ETRS89), a part of the International Terrestrial Reference System 1989 (ITRS89), which is fixed to the Eurasian Tectonic Plate.

Test measurements conducted by the University of Hanover, Geo++, and federal surveying authorities for the city of Hamburg have shown that the accuracy

SAPOS Service level	Availability	Data transfer	Accuracy	Update rate	Data format	Fee
EPS	Real time	UKW/RDS LW	1-3 m	3-5 s	RTCM 2.0 2)	Relating to receiver type
	Real time	2m radio partly GSM 1)	1-3 m	1 s	RTCM 2.0	150 Euro/year
HEPS	Real time	2m radio partly GSM	1-5 cm	1 s	RTCM 2.1	0.1-0.2 EURO/min.
GPPS	Near real time Postprocessing	GSM Telephone Data logger	1 cm	1 s	RINEX 3)	0.2-0.8 Euro/min
GHPS	Postprocessing	Telephone Data logger	< 1 cm	1 s	RINEX	

Fig. 3. SAPOS service levels.

relying on GPS error-factors (i.e. ionospheric/atmospheric influence and orbit parameters) can be highly improved with differential techniques. The quality of the augmentation is dependent on the distance of the mobile receiver to the reference station.

Other differential correction data for Germany can be obtained from the following.

- DGPS Service of Telekom and the German Office for Cartography and Geodesy in Frankfurt/Main. Broadcast area, 600 km in diameter.
- DGPS Service of the Administration of Waterways and Shipping. Broadcast stations, Heligoland and Wustrow. Broadcast area, 180 km in diameter.

4.2.2. Eurofix

Eurofix was developed by the Delft University of Technology in the Netherlands. It uses Loran-C (Long-Range Navigation) to broadcast DGPS corrections. The correction data are modulated on the Loran-C signal without interfering with the Loran-C navigation function.

The first Eurofix transmission station was the Loran-C station at Sylt (Germany). An extension of the system to the Northwest of Europe will be achieved with the stations Lessay (France), Vaerlaendet and Boe (Norway). An expansion to all stations of the North West European Loran-C System (NELS) is under discussion. Further extension in Europe will be possible by using the Loran-C chain in the Mediterranean Sea area and the Russian Chayka (Loran-C equivalent) infrastructure.

The use of Eurofix offers many advantages. The users can navigate with both Loran-C and DGPS, and compare the two positioning results. The possibility for error monitoring is thus good, and the reliability of the system overall is improved. If one system fails, the other can take over and further navigation is possible. The integration of the Loran C and the DGPS system allows a Loran-C station to act like an additional satellite, meaning a three-dimensional position can be calculated with less than four GPS satellites in view.

The Eurofix coverage range is estimated to be at least 1000 km from each equipped Loran-C transmitter. Fully implemented, an absolute accuracy < 5 m and an availability of more than 99.9996% per month is achievable in most places.

4.3. Other countries

For Norway, the SATREF (SATellittbasert REFeransesystem) concept includes a complete network of DGPS reference stations. The network is comprised of multiple DGPS reference stations; transmission of corrections; networking, and monitoring. Typical applications include the nation-wide DGPS coastal reference network, and private DGPS networks with transmission of corrections via INMARSAT or VHF radio links. The Norwegian Mapping Authority, which implemented the system, chose a 64 Kbit/s data Ethernet for the SATREF communication. Raw data and differential corrections are continuously transmitted from each reference station to the control and monitor centre. Control of each reference station is also available via the Ethernet. Important to the SATREF system philosophy is the independence of specific GPS manufacturers in deriving the differential GPS data at the reference station. Therefore, GPS range and velocity observations together with ephemeris and almanac data are used by the SATREF reference station software to compute the corrections. This means that the SATREF can interface with any commercially available GPS receiver providing external access to the GPS observations (http://web.sol.no/seatex/posi/satref.html, 1998).

In Switzerland, the Federal Office for Topography maintains a DGPS service (SWIPOS) in co-operation with SWISSCOM (Swiss Communication Provider). Correction data is sent out by FM-Radio/RDS (Radio Data System). At the moment, six FM stations are in operation. An accuracy of about 1–10 m can be achieved, real-time applications are supported, and a variety of receivers are available (http://www.swisstopo.ch, 1998).

In Italy, five GPS reference stations are in operation: Matera, Noto, Bologna, Cagliari, and Venice. The GPS station in Genoa is under construction. The GPS receivers (Turbo Rogue SNR 800) of this permanently operating network have been installed at these locations for geo-physical reasons. Matera also has VLBI (Very Long Baseline Inferometry), SLR (Satellite Laser Ranging) and PRARE (Precise Range and Range Rate Equipment) stations. Noto and Bologna are connected to VLBI, and Cagliari and Medicina have a SLR connection. Venice and Genoa were chosen because of their vicinity to a tide gauge. The installation of a GPS receiver in Lampedusa is under investigation. Most of the GPS reference stations are collecting meteorological data on pressure, temperature and humidity in addition to the GPS data. The main goal of the Italian network is to service the geodesic and geophysical scientific community. Venice and Genoa are also suitable for mean sea level studies as well as DGPS. Data from all stations, downloaded by modem, is collected in Matera, where the master station and computing centre are located. Matera also forwards data to the EUREF (European Reference System) on a weekly basis. Financial support comes exclusively from the Italian Space Agency.

In the UK, a public DGPS service began operating in August 1998. This service is provided by Trinity House and the General Lighthouse Authorities (GLA) for Scotland and Ireland. The service is financed from “light dues” charged on commercial shipping and other income from the General Lighthouse Fund. The reference network consists of 12 stations providing coverage of up to 50 nautical miles around the coasts of the UK and the Republic of Ireland. Commercial DGPS services are also available for 85% of the UK. The commercial service is available 24 h a day, 365 days a year. To ensure a high level of quality for the service, the performance of the reference station and the quality of the data-broadcasting RDS signal are monitored as well as the GPS status. Should safety margins be exceeded, users are informed by the control centre (http://www.lighthouse-development.org.uk).

The European Reference (EUREF) network was installed to achieve complete DGPS coverage for Europe. In May 1996, the number of tracking stations included in the EUREF network was approximately 40; now nearly 60 stations are part of this network. Since May 1996, 20 permanent GPS stations have been included in the EUREF network. They are located in Austria (one station), Finland (three stations), Germany (one station), Italy (one station), Latvia (one station), Norway (four stations), Poland (two stations), Russia (one station), Slovak Republic (one station) and Sweden (five stations). The Finnish Geodetic Institute maintains FinnNet, from which three sites were selected to be integrated into the permanent EUREF network. The Norwegian SATREF network includes the IGS sites Tromsø and NY-Ålesund. Four other sites have been selected for inclusion in the EUREF network: a network of 21 permanent GPS reference stations, SWEPOS, has been established by the National Land Survey Office in Sweden, and the Onsala Space Observatory. Besides the IGS stations in Kiruna and Onsala, five sites from SWEPOS were included in the EUREF network.

A station can officially be recognised as a EUREF station if:

- the station is installed in accordance with IGS standards;
- the station log file is available at the EUREF permanent network central bureau;
- data from the station are available to the EUREF community;
- data from the station are routinely analysed by one of the EUREF analysis centres (http://www.oma.be/ISB-ORB/EUREF/papers/euref97/node2.html, 1998).

In addition to companies providing DGPS services on the national level, several provide international services in Europe and world-wide. OmniSTAR (a part of the FUGRO consortium) maintains a world-wide network of reference stations, providing differential correction data for almost every continent. The data is broadcast by geostationary satellites. An accuracy of better than 1 m can be achieved within 1000 km from the reference station, and within 2000 km, an accuracy of less than 3 m can be achieved. The correction data signal availability is $> 99.98\%$ and the update rate is < 10 s. A “virtual base station technique” is used to ensure the high accuracy standard. The user community is supported with a 24-h hotline. The use of OmniSTAR DGPS data for agricultural applications was tested with good results. Limitations in availability may occur if the reception of the geo-satellite is obstructed.

5. Future GNSS developments

The need for a civilian satellite-based system has particularly been voiced in Europe, because both existing systems are under the control of foreign military forces. The future concept of a GNSS and differential augmentations (DGNSS) should guarantee that the signals remain available on an unrestricted basis, and that performance will be maintained at all required levels.

The European Tripartite Group (ETG) was formed to manage Europe’s contribution to GNSS-1. It brings together the European Organisation for the Safety of Air Navigation (Eurocontrol), the European Space Agency (ESA) and the European Commission (on behalf of the European Union). Each organisation contributes experience, expertise and funding to the programme.

- European Commission: responsible for institutional/policy matters and co-ordination.
- Eurocontrol: responsible for defining mission requirements for civil aviation.
- European Space Agency: responsible for GNSS development, deployment and technical validation activities.

The immense cost of development, implementation and maintenance of new satellite-based navigation systems means that agricultural users will probably not be able to establish a separate system. Agricultural applications will have to be based on systems primarily developed for other applications such as aviation, maritime or land traffic. For this reason, it is important to highlight the agricultural needs now to influence the ongoing developments as much as possible. The EC and ESA are responsible for the development of GNSS-2.

5.1. GPS Accuracy Improvement Initiative

At the moment, the GPS space segment is controlled by the Master Control Station at Colorado Springs and four additional monitor stations, located at various locations near the Equator. These stations determine the orbit and clock parameters influencing the accuracy of the positioning.

The goal of the Accuracy Improvement Initiative is to increase the number of monitor stations. In the first step, six additional stations will be established and another eight are planned. These stations are maintained by the National Imagery and Mapping Agency (NIMA, formerly Defence Mapping Agency (DMA)). With more frequent measurements, higher accuracy of orbit and clock parameters can be obtained and, also, more uploads to the satellites.

Analyses have shown that a 50% improvement in accuracy can be achieved. At present, this advantage is only of benefit for military users (for SA reasons). The Accuracy Improvement Initiative should be completed by the year 2000.

5.2. Galileo

As already mentioned, the European user community identified the need to build an independent European Satellite Navigation System. The GNSS Forum was established to work out an appropriate approach, and a comparative system study was performed. The working-group results of the GNSS Forum and the final report of the chairman were delivered to the European Commission in December 1998. These papers, as well as the parallel-worked technical-orientated ESA studies, formed the basis of the communication of the Commission, which was published on 10 February 1999. The paper presents the strategy for European involvement in the next generation of Global Navigation Satellite Systems (GNSS-2) and for participating in the corresponding markets. The communication's advice is to build-up a European navigation space-segment and respective ground infrastructure under the designation “Galileo”.

The policy for this decision is to overcome the unacceptable dependency on third states, which means, currently, the US operating the GPS. The most critical consequences of this dependency are the problems of sovereignty and security emerging if Europe uses foreign-controlled navigation systems for critical security applications. The inability of the current systems to meet all of the technical requirements of private and commercial users is another disadvantage. It is also important to guarantee that future changes in signal design do not lead to risks for the European user community. The probable introduction of user-fees for both GPS infrastructure and services should also be considered. In the short-term, users would be hard pressed to avoid paying user fees or develop alternatives, if the system presents a "quasi-monopoly". Another argument for the new system is to ensure the participation of European industry in the fast-growing market of satellite navigation. With the expected competition in the field of service provision, European players would have the disadvantage of having no access to the technical development of the system itself.

The communication of the European Commission indicates that Galileo should be a global system with an open architecture, compatible with GPS on the one hand, and completely independent on the other. The Russian Federation is expected to play a major role in the realisation of Galileo.

Galileo's space segment should be based on Medium Earth Orbit Satellites. The costs are expected to be between 2.2 and 2.9 billion Euro, depending on the final constellation. The financing will be a shared public-private partnership. The legal framework for private investment has yet to be clarified.

The possibilities for the realisation of this system were considered under the following aspects.

- Development of a GNSS in co-operation with one or more international partners (especially the US or Russia).
- Independent development of a GNSS by the European Union (EU).

In the course of the evaluation, it became clear that joint development is more economical. Such co-operation must, however, meet a variety of criteria including guarantees for unlimited and uninterrupted service, qualified involvement in the design, development and operation of the future GNSS, as well as a comprehensive and equal role in the control of the system. Furthermore, European industry must have a fair chance for unrestricted competition in all market segments.

Numerous talks with various partners on the topic of joint development showed the Commission that the US is unwilling, for military reasons, to share control of GPS. They would, however, be prepared to co-operate in certain technical areas. The US partners also acknowledge that two complementary systems (GPS and Galileo) would strengthen the overall system, thus enabling the use of satellite navigation and precision timing for certain applications e.g. as the sole means of navigation in certain modes of operation, or under unfavourable conditions (e.g. in cities).

Consultations with the Russian Federation revealed that an effective and comprehensive partnership for the development of a new international civil system on the basis of today's GLONASS is possible. One important advantage of such a partnership is that the EU would benefit from Russian experience in the fields of operating and controlling a satellite navigation system. In addition to the ability to deploy a separate, robust system more quickly, the joint use of valuable GLONASS frequencies would be possible.

The Galileo proposal consists of a core constellation of medium earth orbit satellites with respective infrastructure, and specially designed terrestrial systems. This concept was chosen because experience with existing systems minimises technical risks. This would especially hold true if the co-operation with the Russian Federation can be established on a satisfactory basis. The global approach was chosen to secure a fair share of the global market with its potential for hardware and services for European industry.

In an analysis of various possibilities for financing such a system, it was determined that as long as the US continues to provide its basic GPS signal free of direct user fees, public funds would be needed to establish Galileo. The following three-component financing was suggested:

- significant public funds from the EU within the framework of existing budgets of the TEN projects and from ESA should be made available;
- further sources of income should be created which will require regulation;
- a public–private partnership allowing for outside (private) investments, offering satisfactory returns, should be created.

A public–private partnership would take into account that Galileo will be used for public services and allows for privately operated services. It is the express aim that Galileo generates sufficient revenue to cover costs arising in the operation phase (140–205 million Euro/year) (Bundesministerium für Verkehr, Bau- und Wohnungswesen, 1999; European Commission, 1999).

6. Precision navigation for guidance in agriculture with GNSS

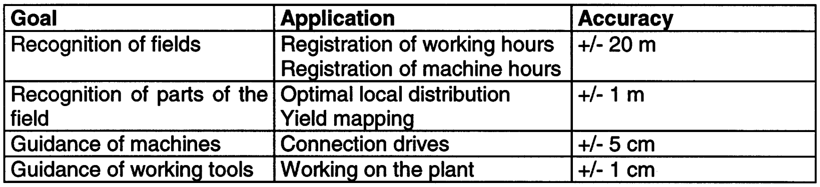
Modern navigation technologies have had a great impact on current agricultural technologies. Combined with a Geographic Information System (GIS), this new technique is used for field mapping, yield mapping, farm management, etc. “As a technology-driven enterprise, precision farming breaks into three categories of tools:

- The crop, soil and positioning sensors—including remote and vehicle-mounted, on-the-go tools that detect moisture levels, protein, water stress and disease or weed infestations.
- The machine controls that control field equipment and can vary the rate, mix and location of water, seed, nutrients or chemical applications.
- The computerised GIS maps and databases that process the data produced by the first category of tools and generates the ‘prescriptions’ that drive the second category.” (Gibbons, 1997)

A good overview on this subject is published in *Computers and Electronics in Agriculture* (Auernhammer, 1994). For more detailed information concerning the use of GIS in agriculture, see Earl et al. (1999).

In agriculture, satellite navigation systems offer the opportunity to:

- measure position in metre range, e.g. for precision farming;



Goal	Application	Accuracy
Recognition of fields	Registration of working hours Registration of machine hours	+/- 20 m
Recognition of parts of the field	Optimal local distribution Yield mapping	+/- 1 m
Guidance of machines	Connection drives	+/- 5 cm
Guidance of working tools	Working on the plant	+/- 1 cm

Fig. 4. Required accuracy for agricultural applications.

- measure position in centimetre range:
  for guidance in agriculture;
  for surveying (GIS);
- measure true ground speed;
- measure attitude to cancel out vehicle movement on rough terrain.

Measuring the position with centimetre accuracy is not sufficient for guidance purposes; the attitude must also be measured. The position measurement is made with reference to the mounting point of the antenna, and this mounting point will commonly be selected to minimise shading, reflecting and to enhance electromagnetic compatibility, etc. For this reason, the highest point on a tractor, such as the roof of the cab, may be a preferred location. In view of the vehicle movement caused by a rough field surface or sloping terrain, this could be an unfavourable place. Attitude measurement is unavoidable to compensate for the tractor movement caused by the terrain (see Bell and Speckmann, 1999).

Required accuracy for an application of satellite navigation in agriculture is shown in Fig. 4 (Jürschig and Beuche, 1992).

The use of differential correction data is necessary to obtain such high accuracy. The enormous technical know-how and financial costs for maintaining a personal DGNSS reference station make it more economical for farmers to buy this information from a commercial or public service provider (as mentioned in Section 4.2) The provision of DGPS data is a big market in the US at present. The price of a high quality sub-metre reference station is about US$ 6500–10 000, and for centimetre level accuracy it is up to US$ 20 000.

The investment in GIS is much less, but also requires some training. Farmers should either form working groups to share GIS equipment or use service and database maintenance from a private company. Hardware prices are dropping steadily, and the GIS market is concentrating more and more on systems able to work in a PC architecture. The combination of different thematic maps (soil, ground moisture, yields, etc.) is simple for the GIS to calculate, and some inexpensive or mid-level products can satisfy the needs of most users. The most time- and cost-intensive factor in the GIS administration of a farm is the data recording and the permanent update of this spatial database. Generally, the costs for a GIS system are similar to those shown in Fig. 5 (Bill and Fritsch, 1991).

Fast development in the field of satellite navigation and the growing demand for differential correction data, not only for agricultural applications, but also for use in transport telematics, surveying, avionics, etc., will improve the situation for

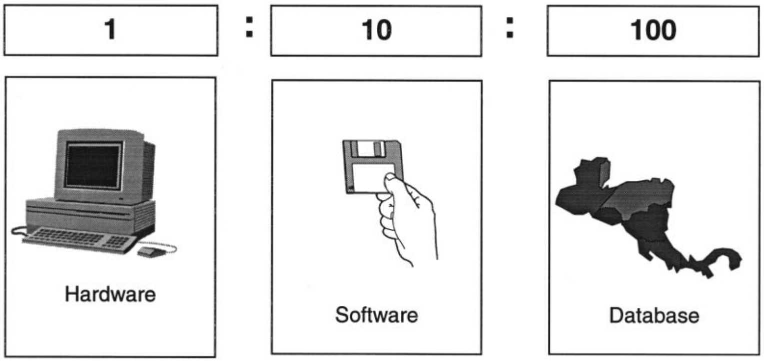


Fig. 5. Cost relationship of a GIS (Bill and Fritsch, 1991).

agricultural GNSS users. The research and development phase for precision farming is almost completed and the commercial market, as it exists in the US today, will take over in the next few years in Europe. The new technology offers the farmer a possibility to work more efficiently, to fulfil his obligation to protect the landscape, and to avoid negative impacts on soil, groundwater and foodstuffs.

7. Conclusions

The developments in satellite-based navigation can be summarised as follows. Hardware allowing for centimetre accuracy is suitable for machine guidance. It can also be used for precision farming, which demands only meter accuracy. On the other hand, hardware sufficient for precision farming is not adequate for machine guidance. New systems will improve the accuracy, availability and integrity for navigation users. The use of differential techniques, important for applications of machine guidance, as well as for attitude measurement will be possible. The on-going activities in GNSS will improve the use of satellite navigation in agriculture.

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