10 Satellite Navigation

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The 21st century is often also considered the "*century of information.*" However, what would information be without a date, time and location? It needs a "*position and time stamp*" in order to create value-added services and is now becoming part of a more general concept, that of "informability" where users receive information tailored to their needs and referenced to location and time.

Satellite navigation delivers positioning and time, independent of weather, around the globe and in space near the earth, 24 hours a day. It is thereby more efficient in terms of accuracy, availability[1], integrity[2] and continuity[3] than any other terrestrial sensor or method.

10.1 Satellite Navigation in the Context of Space Sciences and Applications

Satellite systems presently available and used for positioning, navigation and timing are: the *U.S. Global Positioning System (GPS)* and to a lesser extent the incomplete *Russian Global Navigation Satellite System (GLONASS)*. The European satellite navigation system *Galileo* is under development and might be completed around 2010 (see boxes later in this chapter).

Satellite navigation technology is increasingly used in almost all sectors of activity. Its high performance standards already make it an essential tool for very demanding professional, commercial and scientific applications. Converging factors have favored this remarkable expansion. The availability of communication networks and Geographical Information Systems (GIS), together with the overall decrease in the cost, size and power consumption of satellite navigation receivers have driven the market towards high-volume consumer applications. The public sector, for example the European Commission, but also worldwide bodies in different fields of application are setting up more and more regulatory frameworks which promote the use of satellite navigation services to improve the safety and efficiency of all types of transport modes (rail and road, maritime, aviation).

Moreover, nowadays applications of very precise satellite positioning can be found in surveying, geodesy and other fields of earth science (geodynamics, weather and climate), whereas very accurate

[1] *Service Availability* represents the percentage of time averaged over the design lifetime (20 years) when the service is within the specified performance (accuracy, integrity and continuity) for any point within the service volume. It is derived from the availability of each operational configuration (nominal, without failures, or non-nominal, with one or more failures), weighted by its probability of occurrence, averaged over the design lifetime.

[2] *Integrity* is defined by the following parameters:

- Alert Limit: the maximum allowable error in the user position solution before an alarm is to be raised within the specific Time-to-Alert.
- Time-to-Alert: the time from when an alarm condition occurs until the alarm is received at the user level (including the time to detect the alarm condition).
- Integrity Risk: the probability, during any continuous period of operation, that the computed vertical or horizontal positioning error exceeds the corresponding Alert Limit, and the user is not informed within the specified Time-To-Alert.

[3] *Continuity Risk:* the probability that the specified performance (accuracy and integrity) is supported by the system over the time interval applicable and within the coverage area, given that it is supported at the beginning of the operation and predicted to be supported throughout the operation duration.

timing is needed for telecommunications, energy, finance, banking and insurance.

No doubt that a significant military use of GPS also takes place for the guidance of modern weapons. This so-called NAVWAR (Navigational Warfare) application is out of the scope of this chapter on civil applications.

Most people have not yet realized that for the so-called critical infrastructure of our countries we rely on a continuous availability of high-precision time provided by a satellite navigation system at present only GPS. Examples are synchronization in telecommunication base stations, and the supply of energy for networks, banking and financial transactions. For these aspects of modern society, an uninterrupted service is vital for government and economic life. A disruption of satellite navigation services would be a threat to economic, safety and security-related applications (Volpe 2001). A misuse is a threat to national security. Therefore, precautions are taken in each global satellite navigation system to protect services that must not be interrupted; they require spectral frequency separation and secured controlled access. In other words, civil services must be "jammable" without affecting the military and/or security signals of a global satellite system. This terrestrial or airborne jamming is always done locally. Because of the high importance of satellite-based applications mentioned before, any manipulation in the satellites themselves would affect and penalize services and economy outside the theater of operations, and is and will be therefore never done.

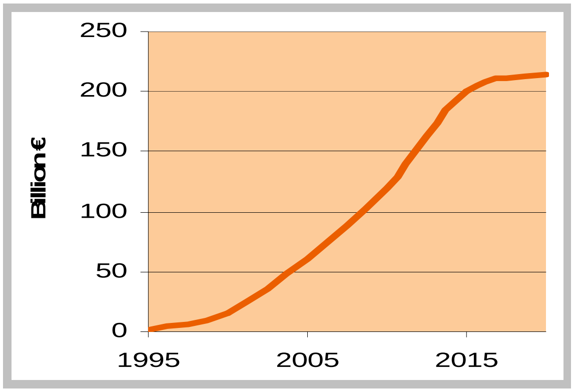


Figure 10-1: Market evolution of global satellite navigation: total annual global turnover (Source: Business in Satellite Navigation, Booklet of the European Commission, European Space Agency and the Galileo Joint Undertaking, March 5, 2003)

Coming back to the growing market in satellite navigation, a few graphs should make this fact more transparent. Figure 10-1 shows the total estimated annual global turnover for satellite navigation over the next decade.

Figure 10-2 illustrates the breakdown in satellite navigation applications. The automotive sector (car navigation) as well as integrated personal communications (satellite navigation chip in a mobile phone) are predicted to be the most dominant application areas.

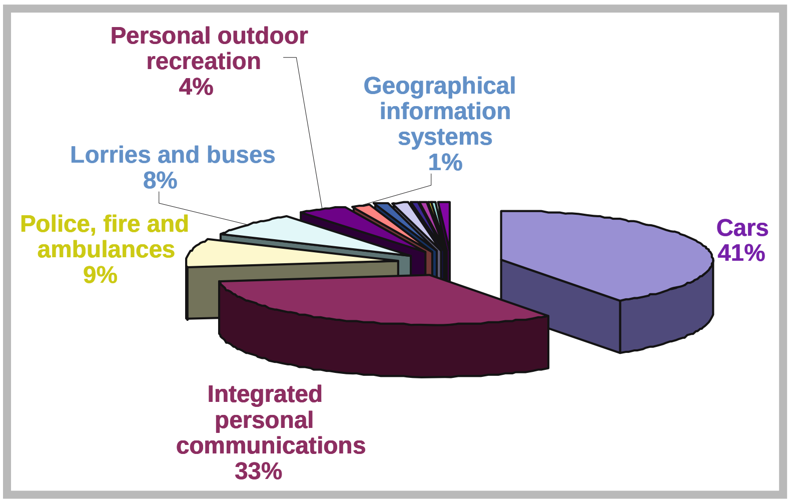


Figure 10-2: Application breakdown of satellite navigation (Source: CBA, European Commission, Nov. 2000)

Considering the information in the figures 10-1 and 10-2, we can conclude that satellite navigation really marks a general breakthrough in the utilization of space**:** Never before has a space project had so much impact on the daily life of each citizen on earth!

However, when trying to establish a business plan for satellite navigation, one is faced with the problem that the immediate products of satellite navigation like position coordinates and velocities cannot themselves generate considerable revenue. Only when building up so-called "value-added services" by combining position and time with communication and geographical information, a successful outcome is guaranteed and any applications can be found.

10.2 Principles of Operations – a Brief Outline

The heart of a satellite navigation payload is a very accurate atomic clock (rubidium, cesium, H-maser) in redundancy generating time signals, or more precisely, *carrier phases* (sinusoidal radio frequency signal) of a certain fundamental frequency (present satellite navigation systems are working in the L-band). On the carrier there is a binary random sequence, a so-called *ranging code* (pseudo-random noise -PRN- codes), modulated with properties carefully selected in order to mainly minimize inter- and intra-interferences. A binary-coded *broadcast message* consisting of data on the satellite orbit, the satellite health status, satellite clock bias parameters and an almanac (approximate positions of the other satellites in that constellation) modulated also on the carrier is transmitted with a low number of bits per second (e.g., 50 bps for GPS) to the user. Satellite clock time is usually aligned to an international time standard, like a real-time prediction of the *Universal Time Coordinated* (UTC) modulus, an integer number of seconds determined by one or several time laboratories of the satellite ground segment.

In order to differentiate between signals from different satellites, access could be arranged in one of the following ways. Code Division Multiple Access (CDMA) assumes that all signals are transmitted on the same frequency, but have different codes (example: GPS, Galileo). Frequency Division Multiple Access (FDMA) uses a separate frequency for each satellite (or at least for those satellites whose signals cannot be received at the same time), but the same code for all satellites (example: GLONASS). Time-multiplexed signals widely used in communication are not of interest in satellite navigation.

When these signals are received by the antenna of a satellite receiver, converted from analog to digital, and demodulated, two types of measurements are possible.

Pseudorange or code phase measurements (figure 10-3). Since the codes are known, replica are generated in the receiver, however, referring to the receiver time scale which is generated by a less accurate and, therefore, inexpensive clock (quartz).

By correlation the code phase shift is measured, which relates to the signal travel time from the satellite to the receiver antenna. Multiplying it with the velocity of light results in the pseudoranges, which still have to be corrected for various error sources like atmospheric refraction (ionosphere and troposphere), orbit errors, etc.

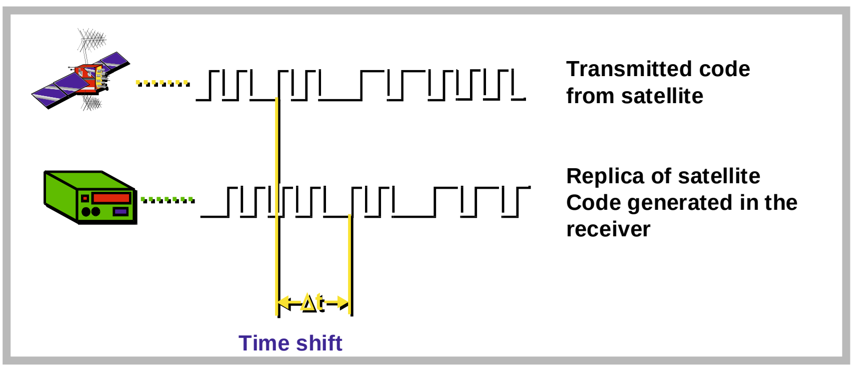
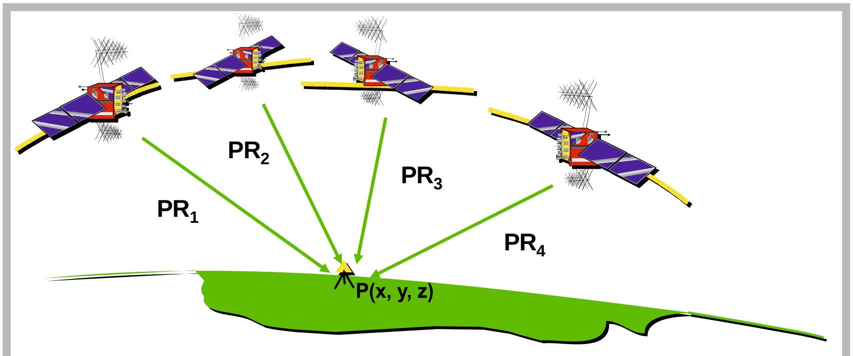


Figure 10-3: Principle of pseudorange measurements: the time Δt between transmission and reception of the signal is measured, using the knowledge of the code structure. The pseudorange value derived in this way equals $\Delta t \cdot c$, referring to the less accurate receiver time scale



$$\sqrt{(x_1-x)^2+(y_1-y)^2+(z_1-z)^2}+c\cdot\Delta T=PR_1$$
$$\sqrt{(x_2-x)^2+(y_2-y)^2+(z_2-z)^2}+c\cdot\Delta T=PR_2$$
$$\sqrt{(x_3-x)^2+(y_3-y)^2+(z_3-z)^2}+c\cdot\Delta T=PR_3$$
$$\sqrt{(x4-x)^2+(y_4-y)^2+(z_4-z)^2}+c\cdot\Delta T=PR_4$$

Figure 10-4: Principle of absolute positioning using measurements PR_i (pseudo- or code ranges). Using the orbital positions (x_i, y_i, z_i) of the satellites i (i=1,…4) the three-dimensional position (x,y,z) and the clock offset ΔT can be estimated

Note that the pseudoranges are measured in two different time scales. In particular, the low accuracy of the receiver time scale has a certain bias to the satellite clock scale. In principle, for a three-dimensional position on earth, three ranges to three satellites are sufficient (three observations and three unknowns). However, because of the unknown time bias a fourth unknown has to be solved and therefore one more observation has to be carried out. This is also the reason that these measurements do not only give a position (and its derivative, the velocity, in a processing filter) - see figure 10-4 - but can also determine time very precise (time distribution, synchronization and timekeeping). Insofar, a satellite navigation system is also a very precise global, all-weather timing system.

Carrier phase measurements (figure 10-5). Analogously to pseudorange measurements, a carrier phase measurement is the difference between the Doppler-shifted transmitted carrier and the carrier generated in the receiver. Carrier phase measurements are ambiguous, because the receiver can

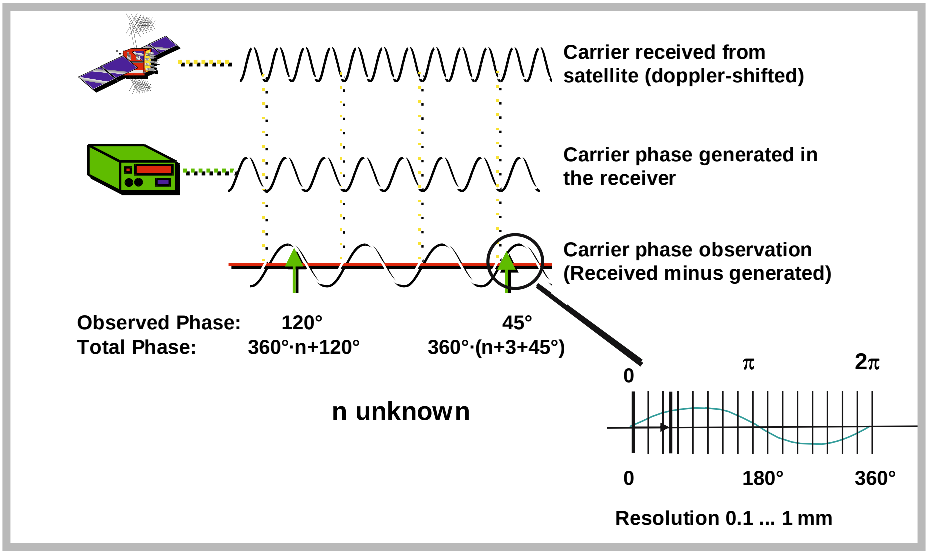


Figure 10-5: Principle of carrier phase measurements: the phase difference between the Doppler-shifted carrier from the spacecraft and the carrier generated in the receiver is measured. Ambiguities arise from integer multiples of the full wavelength, which cannot be determined

measure only fractions of the received wavelength (cycle). This, however, can be very accurately done in millimeters or even sub-millimeters (wavelengths are of the order of two decimeters in the L-band). The unknown cycles, the so-called carrier phase ambiguity, an integer number, has to be determined using least-squares techniques and redundant satellite observations and/or additional information and/or other sensor data. When adding the integer number of cycles, a phase range is derived which, again, has to be corrected for the same error sources as for the code ranges. The determination of the position (and the velocity) of the user is equivalent to that using pseudoranges.

The precise carrier phase data can also be used to smooth the less accurate pseudorange observations in a filter.

Instead of determining the carrier phase *integer* ambiguity separately, pseudorange and carrier phase data can be processed in a combined (Kalman) filter considering the integer ambiguity as an unknown of *real variable* type and solving for it in each observation epoch together with all other unknowns (coordinates, parameter of error sources, etc.). This approach is called "*float solution*," which leads to an ambiguity which is numerically different and "floats" in each observation epoch (which is physically wrong). Nevertheless, this numerical trick leads to two-decimeter-accurate solutions, which avoids the troublesome determination of the integer carrier phase ambiguity.

In order to eliminate further error sources, a differential measurement approach is used; this is a common practice in engineering sciences in order to cancel out (constant) errors by building up differences.

In satellite navigation a receiver is placed at a station with known coordinates. Comparing the observations with the real values derived from that position and the known orbits of the satellites leads to corrections (pseudorange or phase corrections) which the user applies to his observations. This is the key to millimeter accuracies in satellite navigation. Figure 10-6 illustrates the principle of differential GNSS.

Figure 10-7 informs about the present accuracy capabilities of the GPS system down to the millimeter level under ideal static conditions. GLONASS accuracies are similar; Galileo might show even a slight improvement. With respect to timekeeping, time transfer and synchronization with other sensors, accuracies in the nanoseconds level are possible.

For more details on observations and processing strategies the reader is referred to textbooks of satellite navigation (see the references to this chapter).

Standard products of satellite navigation are so-

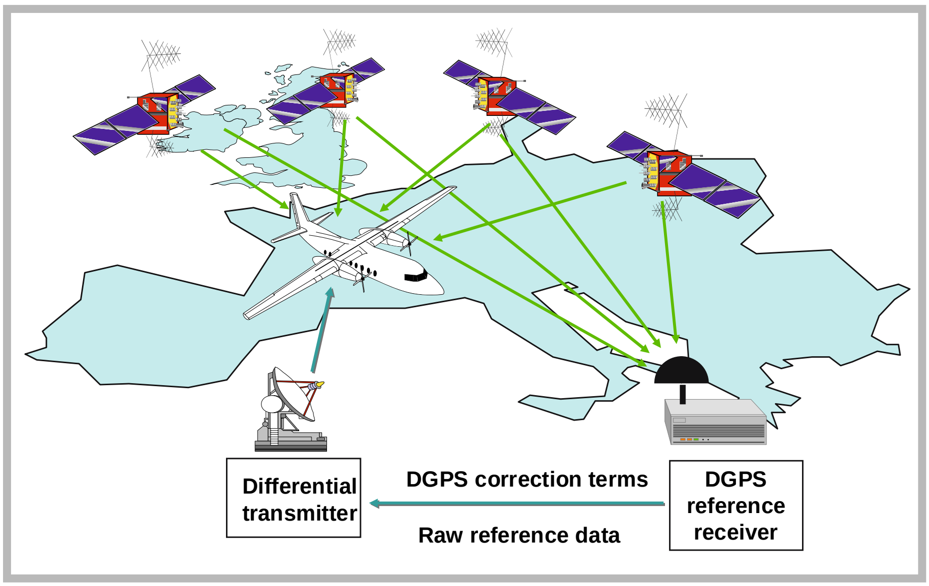


Figure 10-6: Principle of differential mode of GNSS. Here errors of the pseudorange or carrier phase measurements are eliminated by comparing the observed values with those derived from a station with accurately known coordinates and the broadcasted satellite orbits. This method allows for millimeter accuracies of the relative position

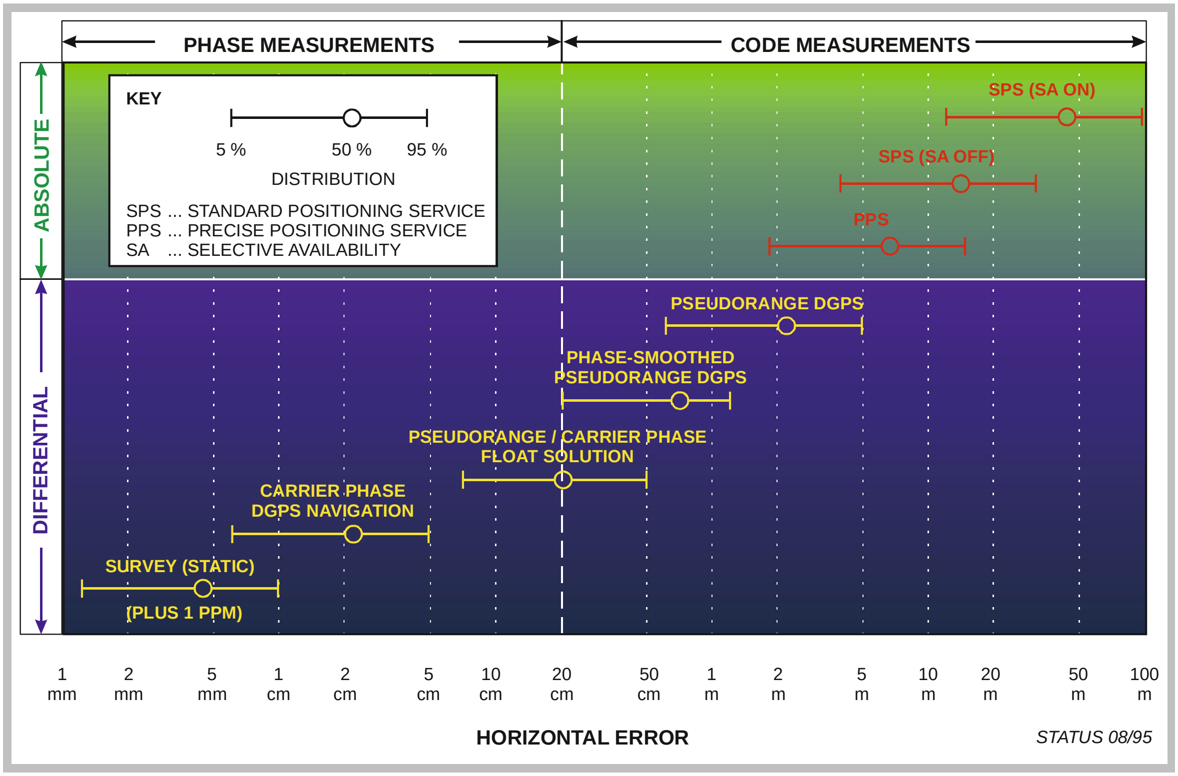


Figure 10-7: Horizontal errors of the Global Positioning System (GPS) in absolute and differential mode and type of processing (DGPS Differential GPS, PPM part per million of baseline length); vertical errors are approximately twice the horizontal errors

called PVT (position-velocity-time) results. The use of more than one antenna enables the user to make attitude determination (in general four antennas for three-dimensional attitude determination).

In recent years, however, many more nonstandard quantities have been derived. When deriving the pseudorange and carrier phase observations it is necessary to apply many corrections, for example atmospheric corrections (ionosphere and troposphere), precise orbit corrections, etc. Since these corrections rely again on other parameters like temperature, pressure, total electron content, etc., one could also consider those parameters - which are sometimes based on hypotheses.- as unknowns in the processing scheme. By doing so, many new products result from satellite navigation. These are described in chapter 10.3.11 under “Science Applications” of satellite navigation.

10.3 Applications

10.3.1 Road Transport

The road sector is a major potential market for satellite navigation. By 2010 there will be more than 670 million cars, 33 million buses and trucks and 200 million light commercial vehicles worldwide. Satellite navigation receivers are now commonly installed in new cars. Using geographical information, positioning, navigation and guidance of the vehicle is carried out with the *aid of satellite positioning and map matching*. Real-time traffic and travel information is provided via radio transmission in order to inform the driver about possible new routes due to incidents like congestion or accidents, for example (figure 10-8).

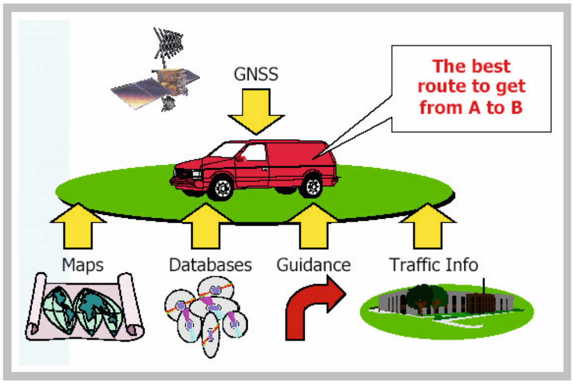


Figure 10-8: Positioning and guidance

Whereas in this first stage satellite navigation in conjunction with a geographical data base asks for no accuracy better than, approximately 30 m (positioning and guidance only), the next step in application aims to locate the vehicle in the right lane of the street (1 to 2 m accuracy through differential GPS), thereby enhancing the safety of the driver in traffic, possibly also by interacting with the car's advanced driving assistance system. In the near future the real-time availability of decimeter accuracies will ultimately lead to collision avoidance (location within the lane).

A very important application is managing emergency and rescue vehicles (figure 10-9). Combined with dynamic traffic information the vehicles can reach the required area much faster. Also, road tolling can use satellite navigation in order to determine distance-dependent charging (under an initiative of the German government a consortium is installing a highway toll system for trucks in Germany in 2004/5).

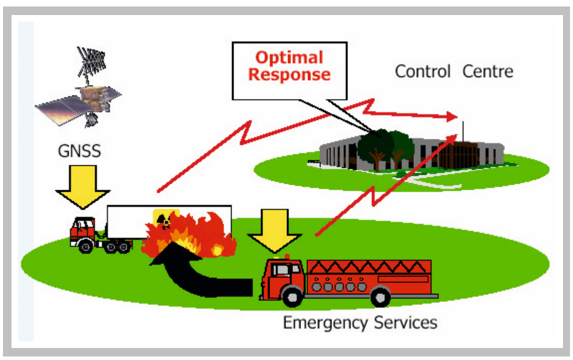


Figure 10-9: Satellite navigation and telecommunication functions for emergency services

Taxi, bus and truck fleet management are crucial and complex tasks for operators. Companies have already equipped more than 500,000 vehicles in Europe with satellite navigation receivers to identify the location of each to a control center. Telemetry and *communication functions are added* for that purpose. Knowing the exact locations of the vehicles, operators can more effectively manage their maximum use and loading (figure 10-10).

10.3.2 Rail

Rail applications of satellite navigation can be grouped into the following areas: (i) train control, (ii) fleet management and goods tracking, (iii) contribution to passenger information, (iv) energy optimization, and (v) track survey.

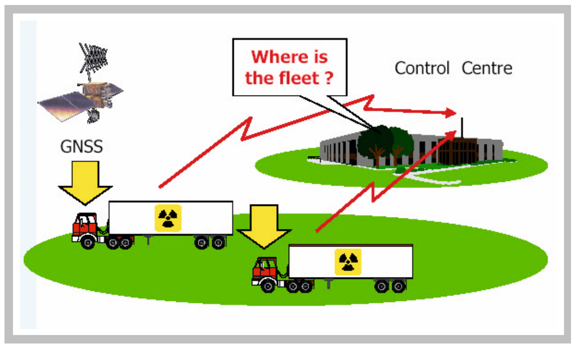


Figure 10-10: Fleet management

Train control. Very high integrity requirements are necessary for this safety-related application. The remaining integrity risk is in the same range (10^{-9}) as in aviation for a precision landing with almost no visibility (CAT III). A satellite navigation system alone cannot fulfill these high requirements; its integrity might be only of the order of 10^{-4} to 10^{-6}. The accuracy requirements are not so stringent. Differential satellite navigation (DGPS nowadays) can deliver the required positions in the 1 to 2 m range. Due to the integrity problem a hybridization of a satellite navigation receiver with other sensors, like odometers, balises and gyroscopes has to be considered. In addition, communication functions have to be added since a satellite navigation system is only a one-way system transmitting signals from the satellite to the user's antenna. All safety-related train control functions are standardized in the European Rail Traffic Management System (ERTMS).

Fleet management and goods tracking. As it is the case also for all other transport modes, fleet management is an important tool for improving the logistics and performance for both passengers and goods transportation. For freight traffic, knowing the location of goods in transit is important for customer confidence in timely delivery. The goods can be tracked if they are connected with the carriers (e.g. traction unit identification). Additionally, satellite navigation may help to organize rolling stock, improve rolling stock maintenance, enable effective goods tracking, simplify route pricing and supervise track usage. Accuracy requirements can be easily fulfilled with a single frequency receiver (5…10 m).

Contribution to passenger information. Information about train arrival and departure times, especially when there are delays, is important for maintaining good service. On-board passenger information is also essential. Knowing the position of the train (low accuracy requirements) can also be the basis for additional services to passengers, such as connections and tourist information.

Energy optimization. Currently, rail movement is generally not optimized for energy consumption. A driver normally controls the train according to a speed-profile table, which generally defines the allowed speed depending on track distance traveled. However, drivers often change speed without concern for saving energy. For example, they brake sharply before a tunnel instead of using regenerative braking at the appropriate distance before the tunnel. In order to save energy, the first question is to know the train's position with respect to its environment. Satellite navigation provides a cost-effective means of offering that information.

Track survey. Surveying and monitoring of tracks is an important task for ensuring safe passage for trains. A good survey needs accurate position determination in the millimeter level and synchronization between the positioning system and other testing/inspection systems. Traditional surveying techniques are replaced by an integration of satellite

Figure 10-11: Track irregularity measurement system investigating the derailment risk of high-speed trains using GPS, INS and Ultra-sonic Sensors (Lück et al. 2001); here: train engine with GPS satellite antenna

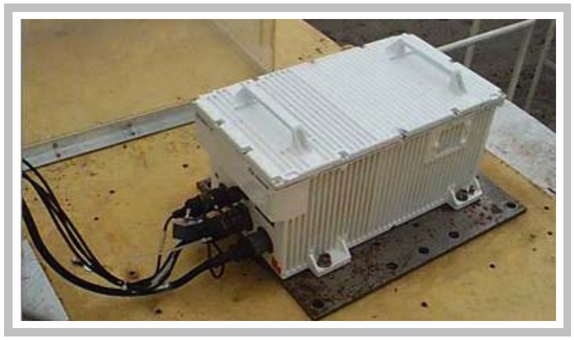


Figure 10-12: Inertial navigation system as part of a track irregularity measurement system investigating the derailment risk of high-speed trains (Lück et al. 2001)

Figure 10-13: Ultra-sonic measuring device as part of a track irregularity measurement system investigating the derailment risk of high-speed trains (Lück et al. 2001)

navigation receivers with inertial navigation systems of very high quality (see figures 10-11, 10-12 and 10-13).

10.3.3 Maritime Navigation

Satellite navigation is used in every phase of marine navigation: ocean, coastal, port approach and port maneuvers, under all weather conditions.

Offshore navigation. The International Maritime Organization (IMO) is implementing regulations on an Automatic Identification System (AIS) and vessel traffic management system in order to increase navigation safety and collision prevention. AIS is using a satellite navigation receiver (among other sensors).

Harbor operations. Approach and maneuvers in ports are critical operations, particularly under poor weather conditions. Locally-assisted satellite navigation is a fundamental tool for all kinds of harbor operations and precision docking. The increased availability of satellites will improve the economic sustainability of operations with satellite navigation in an environment where limited sky visibility might be an issue. Local components in the harbor and communication links transmitting the exact position of vessels will encourage innovative and safe automated operations.

Inland waterways navigation. Satellites provide precise navigation along inland waterways, especially in critical geographical environments or meteorological conditions. This includes navigation on rivers and canals, where the accuracy and integrity of navigation data are essential to automate accurate maneuvers in narrow waterways.

Survey and marine engineering. Satellite navigation has revolutionized hydrographic surveying for dredging and maintenance of harbors and waterways, drilling operations, mapping the sea bottom and underwater obstacles (in combination with an echo-sounder type of sensor), pipe and cable laying, and oil and mineral exploration. Differential GPS in buoys is able to deliver instantaneous sea surface and wave heights in the millimeter level with a frequency of 10 Hz and higher (figure 10-14).

Science. The observation of tides and currents is possible using GPS in buoys or carrying out static surveys at tide gauge stations worldwide, thereby establishing a worldwide unified datum.

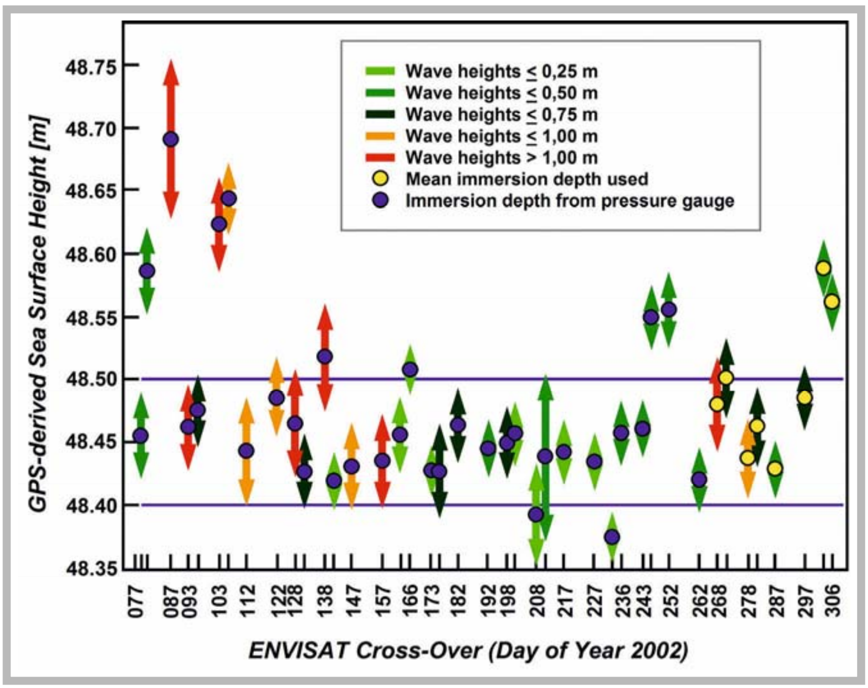


Figure 10-14: Results from the ENVISAT radar altimeter calibration campaign using moored high-sea GPS buoys (heights reduced by tidal and atmospheric pressure impact) (Schueler and Hein 2004)

Search and Rescue. The Galileo satellite navigation system (to be completed around 2010) will contribute to the international search and rescue service, enhancing the worldwide performance of the current COSPAS-SARSAT system (figure 10-15). The positioning accuracy of today's system is very poor (typically a few kilometers) and the alert is not always issued in real-time. The Galileo SAR service will drastically reduce the time to alert, and the position of the distress beacon will be determined to within a few meters. The Galileo SAR service foresees the rescue center's acknowledging the distress message. This will increase victim survivability and reduce the number of false alarms that dog the current system.

Commercial maritime operations. Commercial maritime activities will be assisted by satellite navigation. In fishing, it will help to locate traps and nets, manage fleets, and monitor cargo. Delivery and loading schedules can be optimized via GPS. Even the location of shipping containers can be facilitated, and satellite navigation could be used for automatic piloting of barges.

10.3.4 Aviation

Due to safety requirements commercial air transport has the most stringent requirements on satellite navigation. Table 10-1 informs about the detailed numbers for all phases of flight. It is integrity which

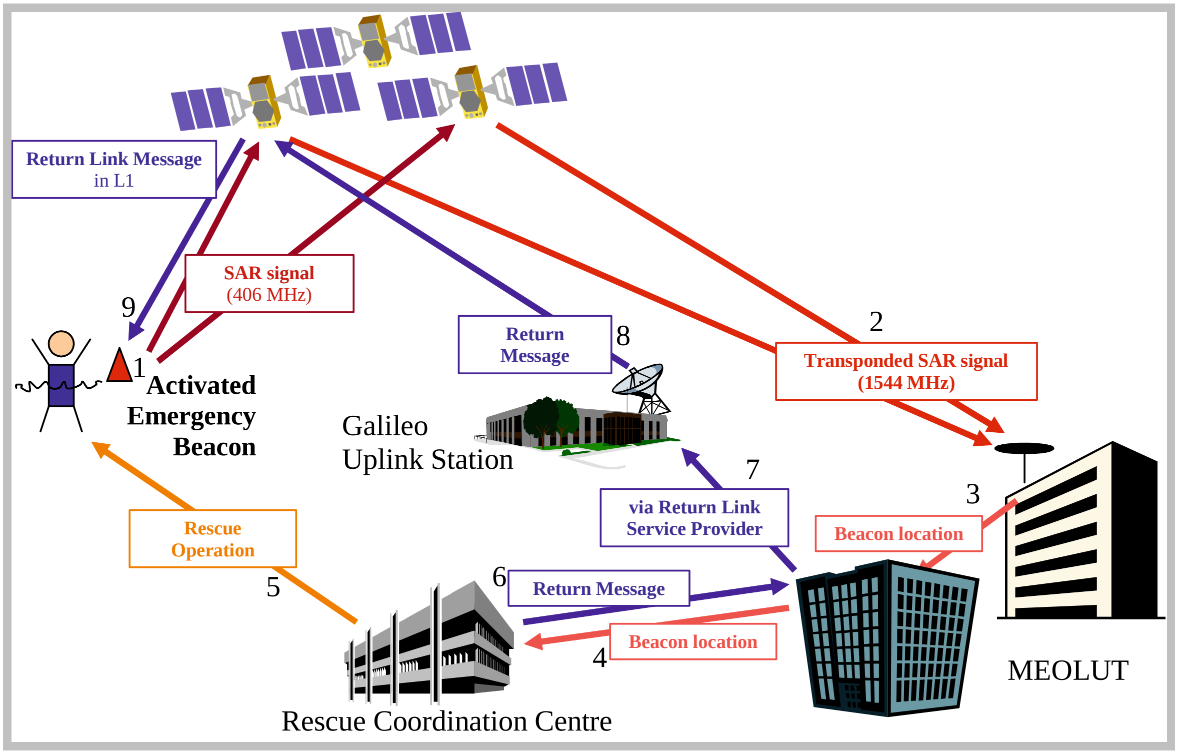


Figure 10-15: Planned search and rescue in the Galileo satellite navigation system. The approach is as follows: (1) The receiver of someone in emergency activates an emergency beacon which sends a search and rescue (SAR) signal in 406 MHz to the Galileo satellite. (2) The SAR signal is transponded by the Galileo satellite and sends the emergency position on 1544 MHz via the so-called MEOLUT center (3) to the SAR Mission control center (MCC). (4) SAR MCC reports beacon location to the Rescue Coordination Center. (5) The Rescue Coordination Center initiates the rescue operation. (6) The Rescue Coordination Center sends a return message via the SAR MCC, the Return Link Provider (7) to the Galileo Satellite (8). (9) The Galileo satellite sends a message to the receiver of the person in emergency in the standard broadcast message

Operation	Accuracy (horizontal 95%)	Accuracy (vertical 95%)	Integrity (probability of HMI)	Time to alert	Continuity Risk (1 - Continuity)	Availability
En Route	3.7 km	NA	10^{-7} / hr	1 min	10^{-4}/hr to 10^{-8} / hr	0.99 to 0.99999
Terminal	0.74 km	NA	10^{-7} / hr	15 sec	10^{-4}/hr to 10^{-8} / hr	0.999 to 0.99999
LNAV (NPA)	220 m	NA	10^{-7} / hr	10 sec	10^{-4}/hr to 10^{-8} / hr	0.999 to 0.99999
LNAV/VNAV	220 m	20 m	$2\cdot10^{-7}$/approach	10 sec	$8\cdot10^{-6}$ / 15 sec	0.99 to 0.999
LPV	16 m	20 m	$2\cdot10^{-7}$/approach	10 sec	$8\cdot10^{-6}$ / 15 sec	0.99 to 0.999
APV-II	16 m	8 m	$2\cdot10^{-7}$/approach	6 sec	$8\cdot10^{-6}$ / 15 sec	0.99 to 0.999
GLS/CAT I	16 m	6 m to 4 m	$2\cdot10^{-7}$/approach (150 sec)	6 sec	$8\cdot10^{-6}$ / 15 sec	0.99 to 0.99999
CAT II / IIIa	6.9 m	2 m	10^{-9}/15 sec	1 sec	$4\cdot10^{-6}$ / 15 sec	0.99 to 0.99999
CAT IIIb	6.2 m	2 m	10^{-9}/30 sec (lateral) 10^{-9}/30 sec (vertical)	1 sec	$2\cdot10^{-6}$/15 sec (lateral) $2\cdot10^{-6}$/15 sec (vertical)	0.99 to 0.99999

Table 10-1: Navigation requirements of the different phases of flight of commercial aviation (Source: Office of Architecture and Investment Analysis (ASD-1), Federal Aviation Administration, Washington, DC)

causes the biggest problem, the required accuracy is no problem. The integrity risk for precision landing with almost no visibility - so-called CAT III landing - has to be < 10^{-9} with an alert time of 1 sec. A satellite navigation system itself without any augmentations can only deliver integrity of the order 10^{-4} to 10^{-6}. This gap can be overcome only by integration with other sensors, mainly using inertial navigation systems.

The high capabilities of satellite navigation over conventional techniques was expressed at the Tenth Air Navigation Conference in 1991 when the International Civil Aviation Organization (ICAO) endorsed recommendations of its Future Air Navigation Systems (FANS) committee and recognized that the primary stand-alone navigation in the 21st century will be provided by the Global Navigation Satellite System (GNSS). GNSS as a generic term for all kinds of satellite navigation systems was born. During the last decade it became clear that the use of satellite navigation would require more time due to regulatory and certification issues. Nevertheless, the idea is still to have a satellite-based gate-to-gate navigation concept.

Meanwhile GPS is certified for en-route flight and non-precision approach enabling aviation now to have more flexible routes, savings in fuel and time, and more aircraft airborne than ever before when using only terrestrial navaids. In the future, higher accuracy and service integrity will allow aircraft separation to be reduced in congested airspace, to cope with traffic growth (free flight concept).

For airports not equipped with instrument landing systems, so-called *wide-area differential* satellite navigation systems or *augmentation systems* were and are being built (2004) in order to allow a precision landing for CAT I (see table 10-1). Monitor stations at known locations are tracking the GPS satellites and send their information to control centers where (i) wide area differential corrections are determined, (ii) errors in the satellite broadcast data are detected and as a consequence so-called “unhealthy” satellites are flagged and integrity messages per satellite are formed (use/do not use/not monitored) and (iii) GPS-like navigation signals are generated. Geostationary satellites (INMARSAT) transmit these integrity messages and the GPS-like signal via the onboard transponder to the user where increased integrity (of the order of 10^{-6} to 10^{-7}) and availability (more GPS signals due to the geostationary satellites) can be obtained. Three of these wide area augmentation systems are established: in Europe EGNOS (European Geostationary Navigation Overlay System.-.see also figure 10-16), in North America WAAS (Wide Area Augmentation System), and in Japan MSAS (Multi-Transport Satellite Augmentation System).

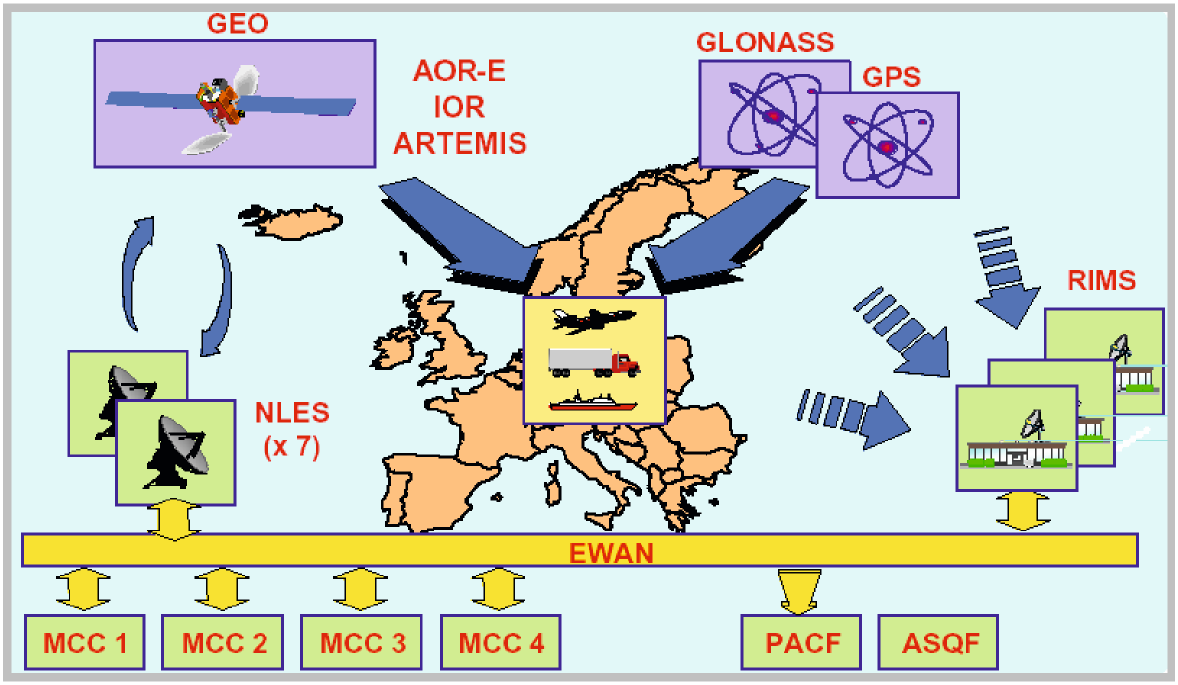


Figure 10-16: The European Geostationary Navigation Overlay System (EGNOS)

Efforts are on the way to apply satellite navigation (in combination with other sensors) for CAT III approaches using local area augmentation systems called LAAS (local differential GPS system at airports) and perhaps pseudolites (terrestrial signal generators transmitting a GPS-like signal).

Monitoring and Surveillance. Position, heading, speed and time information are needed by air traffic controllers for the continuous management of all aircraft. Some areas of the world lack the appropriate ground infrastructure, including secondary radar and communication links.

Taxiway guidance. Moving an aircraft on the ground requires assistance from the air traffic controllers. The airport may have surface radar, but sometimes the taxi movements are reported manually by the pilots and the aircraft is managed using visual aids only. Severe accidents have occurred during this supposedly safe phase. Satellite navigation together with its local elements and communication links (required accuracy 1 to 2 m) will improve the safety of these operations, creating the means for integrated surface movement guidance and control.

10.3.5 Space

Orbit determination of LEO (low-earth orbiting) satellites is usually carried out using dynamic (force) models. Mainly because of the limited knowledge of the near earth gravity field, but also due to other force model parameters, *dynamic* orbit determination is not highly accurate, in general. Therefore, nowadays all LEO satellites carry a GPS receiver making use of the *kinematic* determination of the orbit by satellite navigation. The results can even show centimeter accuracies when employing differential techniques with regard to ground stations. A well-known processing technique is also to smooth the single kinematic GPS solution by a dynamical model which is often called “reduced dynamic mode” (see for example Gill and Montenbruck, 2004, Martin-Mur, 1995, Parkinson and Spilker, 1996).

Using more than one antenna attitude measurements also become possible.

Such an approach is in general only possible if the altitude of the satellite is below the GPS satellites (<20,000 km above the earth). However, it was shown by Balbach et al (1998) with a GPS receiver on the Equator-S mission that even above those altitudes GPS signals can be received which are bypassing the earth from the other side. Insofar, an orbit determination in space was possible up to approximately 60,000 km altitude above Earth.

Future third generation satellites of GPS-III (after 2010) will also carry an additional antenna pointing into space in order to enable also more earth-distant orbit determination.

10.3.6 Telecommunication

The need to *locate callers* has two main drivers: (i) emergency calls (E-112 in Europe, E-911 in US) and (ii) new services based on the location. The first arises through new legislation in several countries aiming to offer efficient emergency services to their citizens by precise and fast response to distress calls. The second is more commercial and points to increasing traffic in the coming years. Technically, location can be achieved by integrating a satellite navigation receiver in the mobile phone (handheld solution) or by using the communication network itself. The last approach is not favored because it would require enormous additional costs for the infrastructure in the communication network. Once the caller's location is known, a great number of services can be offered. Some of these services are:

Location Based Services (LBS). At the beginning of this chapter on satellite navigation, it was already mentioned that information needs to be "time- und position-stamped" in order to create new value-added services in conjunction with geographical information and communication. A classical example is someone asking the way to the nearest hospital. The service provider compares the user's location with the hospital locations stored in a database,

The Global Positioning System (GPS) is a space-based, continuous, worldwide three-dimensional positioning and navigation, velocity and timing system operated by the United States Air Force which met its full operational capability in 1995.

The nominal configuration of the space segment consists of 21 satellites plus three active spares arranged in six 55-degree orbital planes approx. 20,190 km above the earth.

The main navigation payload consists of redundant atomic clocks (rubidium, cesium) transmitting very precise time signals right-handed circular polarized on the two frequencies L1 = 1575 1575.42 MHz and L2 = 1227.6 MHz modulated by a pseudo-random code (binary phase shift keying). For civil purposes a so-called C/A code or Standard Positioning Service (SPS) is provided. Access to the encrypted military P(W) code signals or Precise Positioning Service (PPS) requires authorization by the U.S. Department of Defense.

In order to determine a position, a receiver can measure the signal travel times from four or more satellites (code ranging). Multiplying it with the velocity of light results in the slant ranges to the satellites (pseudo-ranges) which have to be corrected for the influence of the ionosphere and troposphere. Measuring the instantaneous Doppler shift the receiver can also determine the velocity vector. Using the carrier phases itself in order to determine the highest accuracy in position requires solving the carrier phase ambiguities (cycles).

Among other activities, GPS modernization in the next years will offer new signals on a third frequency L5 = 1176.45 MHz and a civil code on L2 called L2C.

and then tells the user the nearest hospital and the fastest route. Service providers could also point customers to restaurants, movie theaters or parking lots. LBS will increase communication traffic significantly and generate important revenue to telecommunication operators and service providers.

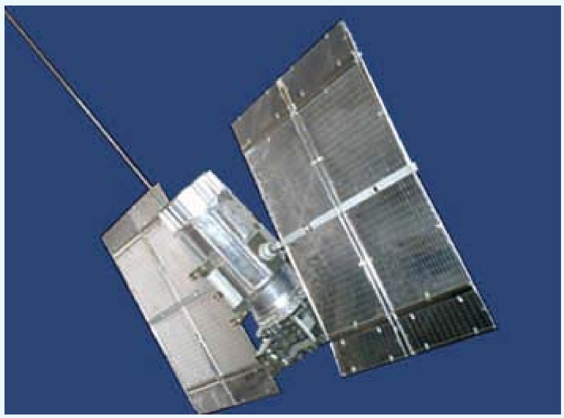
Synchronization in communication networks. Network timing as well as synchronization of telecom base stations is usually done using atomic (rubidium) clocks. Satellite navigation also delivers as a by-product precise time and distributes it worldwide down to the nanosecond level. Precise time-synchronization of the different base stations can significantly increase the traffic capability of the telecommunication systems and the Internet.

10.3.7 Finance, Banking and Insurance

Secure electronic documents. The digital era has created electronic documentation as an effective alternative to paper. This means that new concepts for legal acceptance of electronic signatures and time-stamping must be developed. Satellite navigation provides certifiable and reliable data worldwide. For authentication and electronic-signing, the encryption system could be based on the trusted time signal and the integrity message of the global satellite navigation system, offering the additional value of traceability and liability for the time information.

Data encryption. The latest technologies for electronic encryption rely on highly precise time references - at performance levels obtainable only from atomic clocks - so they are not affordable to mass-market users. The timing service of satellite navigation, in addition to its certification, availability guarantee and integrity message, will enable secure transmission via inexpensive terminals, thus bringing data security within the reach of us all.

Insurance. The financial sector will certainly benefit from the innovations offered by satellite navigation in the field of insurance. It will open up new opportunities and bring about innovative prime and policy conditions. For example, the satellite navigation system could be an effective way of controlling and monitoring valuable goods, including the transportation of gold bullion between national banks, works of art, cash, and any insured risky item. Continuous tracking of these items would reduce risks, thereby creating financial benefits for insurance companies and their customers (e.g., distance-dependent insur-



The GLONASS System is managed for the Russian Federation Government by the Russian Space Forces. Like GPS it is a space-based, continuous, worldwide three-dimensional positioning and navigation, velocity and timing system. The fully deployed constellation is composed of 24 satellites in three orbital planes whose ascending nodes are 120 degrees apart. Eight satellites are equally spaced in each plane. Each GLONASS satellite operates in a circular orbit at an altitude of 19,100 km above the earth with an inclination angle of 64.8 degrees.

The satellites transmit two types of signal: standard precision (SP) and high precision (HP). SP signals L1 have a frequency division multiple access L1 = 1602 MHz + n x 0.5625 MHz, where n is the frequency channel number (n = 0,1.2...). This means that each satellite transmits a signal on its own frequency, except satellites in antipodal slots of orbital planes which use the same frequency.

To determine position, the GLONASS receiver uses the same type of observations and principles as described for GPS. This would also mean that accuracies of GLONASS are in general similar to those of GPS. The GLONASS system is lacking the financial support of Russia and the satellites reveal a relatively short lifetime (2-4 years only). As of 20 July 2004 only 10 satellites were properly working in orbit.

ance charges). Certified satellite positioning would not only provide good legal support for the insurance sector, but also enable a great number of new services, including car and property insurance.

10.3.8 Precision Agriculture and Environment

Chemical spraying. More and more chemicals are being used to increase productivity by controlling pest and weed infestation of crops. Yet, as we become increasingly aware of the environmental impact, there is a need for better management of agricultural land. Besides, spraying chemicals where they are not needed is costly and bad for the environment. How can satellite navigation help? Precise aircraft positioning enables the pilot to spray the herbicides, insecticides or fertilizers in the right places and in the correct quantities. Automatic control also produces a more even distribution, reducing the quantity used. A positioning accuracy of better than 1 m is required. A satellite navigation receiver installed on the spraying vehicles will link the system to a database with other field information. For example, maps can then be generated to show where the spraying occurred.

Crop yield monitoring. Yield monitoring leads not only to effective resource management and consequently significant return, but also contributes to safeguarding the environment. Better control is becoming an issue. Farmers need to be able to map the high- and low-yield areas of fields so that a varying application of chemicals can improve the yield with minimum environmental impact and cost. The yields of individual parcels of land can be monitored every season. Satellite navigation receivers on harvesters will lead to more automated systems and higher accuracy, drawing on the data stored in databases. By looking at yield maps, farmers can see where to take samples for analysis, with the satellite positioning system allowing specific areas to be targeted.

10.3.9 Surveying and Civil Engineering

The surveying community was the first to take advantage of GPS, in particular since many of their tasks have to be solved only post-mission. Nowadays (2004) the term “Real Time Kinematics (RTK)” is often used for offered hardware and software equipment, meaning nothing else than that measurements can be carried out in or near real-time. Insofar it is a special case of “high-precision navigation without guidance.” Although most surveying tasks do not need real-time results it is very important to have a quality control in the field in order to avoid re-surveys and thus save money.

The surveying approach is characterized by the fact that mainly carrier phase observations in differential mode are used in order to achieve the ultimately highest accuracy. Carrier phases have the disadvantage that they are ambiguous with respect to the number of wavelengths (cycles). Therefore special algorithms and strategies have been developed in order to solve this “carrier phase ambiguity” in post-

GALILEO: The European Transport Council decided on 26 March 2002 to build up its own global satellite navigation system consisting of 30 satellites in a mean Earth orbit (at an altitude slightly higher than GPS and a similar inclination as GPS). It will transmit timing signals and a broadcast message on four frequencies in the L-band using Code Division Multiple Access (CDMA). It is envisaged to have all satellites working in orbit around 2010. The position determination follows the principle of GPS. Galileo and GPS will be interoperable for the user through an EU-US Agreement signed 26 June 2004.

mission and even in real-time (often also called “on-the-fly”). Due to the influence of the ionosphere dual-frequency solutions are preferred, but the carrier phase ambiguity resolution is still limited with respect to distances, approximately < 15-20 km, if a success rate near 100% is required (see e.g., Eissfeller et al. 2002; Misra and Enge 2001, pp. 209 ff).

The achieved accuracies in surveying are considered to be 5 mm ± 1 ppm (1 part per million of the measured baseline). However, under ideal conditions millimeter accuracies are possible in post-mission for small baselines, say centimeters, as well as for very long baselines (for example 3,000 km).

Structure Monitoring

Satellite navigation receivers in differential mode on and around bridges, barrages, dams, skyscrapers and historical monuments, for example, can provide important structural monitoring. Satellite techniques can also be used to predict natural events such as landslips, land settling, rising and rock falls, and measure the levels of rivers and lakes. A transmission link ensures the data reach a processing and monitoring center for real-time detection of any movement. Many bridges are carrying average loads higher than predicted during their design, so over the past few years there has been a significant increase in the need to monitor bridge performance. Some bridges are undergoing major repairs and retrofitting to fix critical deficiencies. Satellite receiver technology and data processing software are now cost-effective tools which can be integrated into an automated continuously operating system. Accuracies in the millimeter range are possible for these static networks since the major error source, which is the multipath, can be calibrated with time the system running (Hein and Riedl 2003)

Machinery Guidance

Civil engineers use heavy machinery in many types of construction. Satellite navigation receivers and real-time kinematic techniques can guide these machines precisely to perform their work. The same technique can be used for automated guidance of machines working in dangerous areas or simply to save manpower in repetitive work. The computer compares the actual satellite-derived position with the desired finished terrain, using grid files created from topographic maps. A large, bright display provides visual guidance to the operator for maneuvering the vehicle and positioning the blade to achieve the cut- and fill values needed to match the computer model. A number of surface mines have recently installed satellite-based machine guidance systems with very positive results in productivity and costs.

Construction Site Management and Logistics

During the long construction periods for large structures, it is important to have efficient logistics as well as a coherent and common localization tool. The way the work area is accessed often changes as construction advances, and many vehicles are on the move at the same time. All these activities need efficient management to avoid confusion and wasted time.

10.3.10 Electricity Networks

The growing integration of networks for energy distribution and the emphasis on energy savings and efficiency require increasingly precise and accurate synchronization. Satellite navigation provides network synchronization for power generation and distribution in order to achieve efficient power flow. For that purpose precise timing of satellite navigation is used. Satellite navigation based mapping systems are also used to reduce power outage time by as much as 20%.

10.3.11 Science

Atmosphere-Related Research

Global navigation satellite systems allow for probing the atmosphere of the earth - both ionosphere and troposphere - by ground-based and space-based techniques. The first method requires networks of ground-stations, whereas the second option makes use of low-earth orbiting satellites that carry GNSS receivers.

Troposphere Monitoring (Ground-based)

Precise GNSS carrier phase measurements allow determination of the atmosphere’s integrated water vapor content which plays an important role for the energy balance and the vertical stability of the atmosphere as well as for precipitation forecasts. Water vapor is responsible for about 62% of the natural greenhouse effect and as a consequence, GNSS meteorology has not only become a versatile tool for meteorologists during the past decade, but also for climate researchers.

The basic methodology can be summarized as follows: Carrier phase observations from permanent GNSS stations with precisely known positions are filtered for the tropospheric propagation delay which has the same size on all carrier frequencies used since the troposphere behaves as a non-dispersive medium for microwaves. However, it increases with decreasing elevation angle to the satellite due to the signals traversing longer fractions of the atmosphere. For this reason, the slant path delay is projected into zenith direction using a mapping function and the zenith path delay is estimated in an adjustment process. Conversion into atmospheric water vapor requires knowledge of two important meteorological quantities, namely surface pressure (measured at the antenna site) and the mean vapor temperature. Pressure readings allow separation of the total zenith path delay into a hydrostatic and a wet component, where the hydrostatic delay can be precisely modeled and the wet delay can be directly related to integrated water vapor with the help of the weighted mean temperature. Since this value requires integration of vapor pressure and temperature profiles which are often unavailable, models have been developed to directly derive it from surface temperature measurements.

GNSS water vapor estimation benefits from a favorable error propagation: The conversion factor to transform zenith wet delays into integrated water

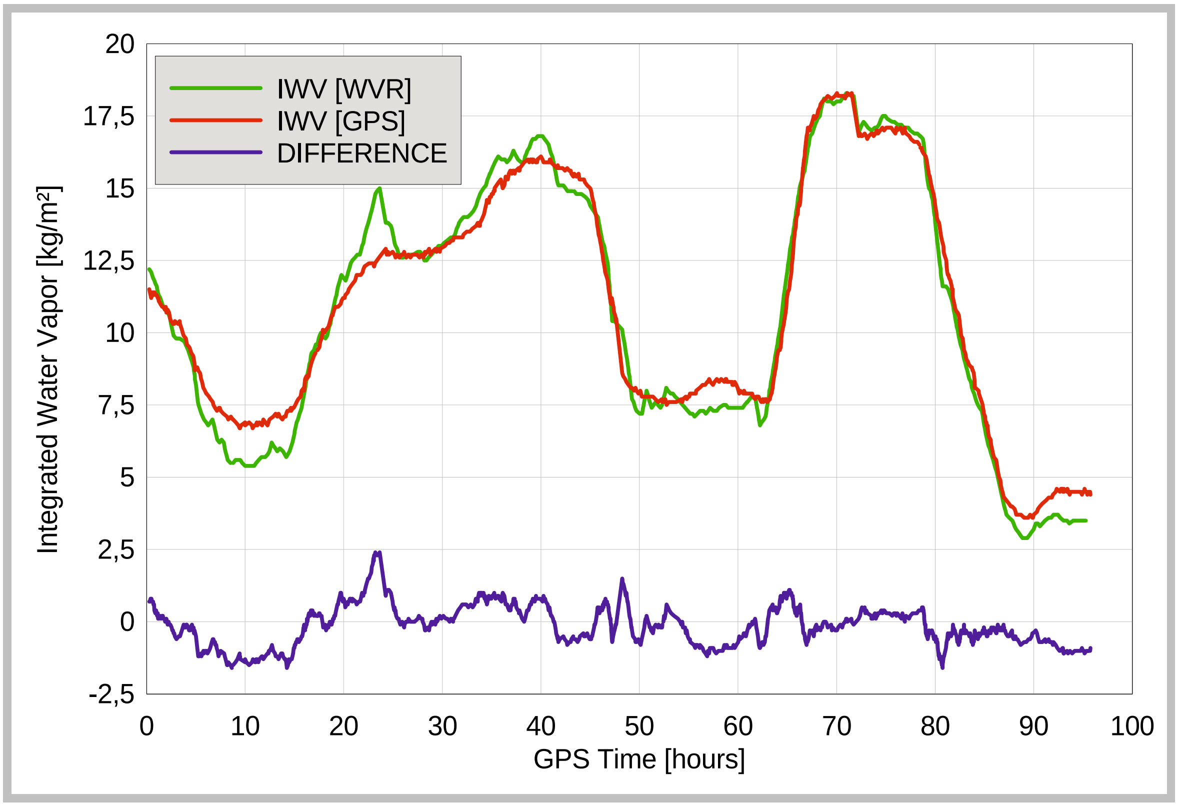


Figure 10-17: Water Vapour Radiometer (WVR) and GPS Signal Diagram, IGS Site Potsdam, start 19 January 1999. Comparison of integrated water vapour (IWV) estimates derived from GPS and measured by a ground-based radiometer near IGS Potsdam station

vapor is in the range of 1:6.3, i.e., if the tropospheric zenith path delay can be determined with an accuracy of better than 1 cm, the resulting error in the water vapor estimate is still in the range of better than 2 kg/m². In practice, an accuracy of 1 to 2 kg/m² can actually be reached, the RMS deduced from figure 10-12 is even slightly below 1 kg/m² (radiometer taken as reference). Ground-based microwave radiometers show a precision which is often slightly better, but their accuracy usually decreases due to calibration uncertainties. In principle, it would also be possible to perform tropospheric tomography yielding a 3-dimensional refractivity field, but this idea suffers from the very dense network of ground receivers required as well as from multipath and signal bending effects that can often not be fully mitigated.

Ionosphere Monitoring (Ground-based)

The idea to monitor the spatial and temporal behavior of the earth's ionosphere is even older than GNSS meteorology, since this part of the atmosphere behaves as a dispersive medium for the waves emitted by the satellites. For this reason, signals are broadcast on more than one frequency, allowing isolation of the ionospheric propagation delay and yielding more precise positioning results. Ionosphere researchers make use of this principle and form a so-called "geometry-free observation" from dual-frequency measurements that allows estimation of the first order ionospheric delay, the by-far dominant effect, whilst second order effects could be sensed by triple-frequency data in the near future. Many approaches generalize the ionosphere as a single-layer model with an effective height about 350 to 450 km. However, in contrast to the wet tropospheric refractivity which is concentrated in the lower few kilometers of the atmosphere, the ionosphere starts at an altitude of about 70 km and extends to an upper boundary layer of 1,000 km. This geometry also allows for ionospheric tomography with inter-station distances significantly smaller than those needed for the troposphere.

Space-Based Methods for Monitoring the Ionosphere and the Troposphere

Probing the ionosphere and troposphere can also be accomplished by means of space-based GNSS methods, particularly by the radio occultation technique. The basic idea dates back to the 1960s when it was practically applied to derive atmospheric properties of several planets of the solar system with the help of satellites that were orbiting those bodies. The Earth-related radio occultation method employs a LEO satellite orbiting at low altitude (700-1,200 km) and carrying a high-performance receiver that senses signals of GNSS satellites which are just about to rise or to eclipse behind the earth. Such a geometry implies that the signal will pass through the earth's atmosphere, where it is significantly bended. The bending angle can be related to the refractivity profile by means of an Abel integral transformation. Since the refractivity profile is a function of electron content, pressure, temperature and humidity (water vapor pressure), it is possible to derive profiles of these quantities. Pressure, temperature and humidity are not of concern when the signals are passing the ionosphere such that even a single-frequency receiver would be sufficient to probe this part of the atmosphere only. When the signals approach the boundary layer between ionosphere and neutral atmosphere, dual-frequency receivers are needed to separate the ionospheric refractivity properly. In the stratosphere, the water vapor term is negligible, whereas it is significant in the troposphere. Regarding the troposphere-related quantities, it should be stressed that temperature and humidity cannot be separated from GNSS measurements alone, i.e., external profile data are needed, such as humidity data from weather models when temperature profile are to be derived. Latest successful missions of this kind were SAC-C and CHAMP, for instance.

Geodynamics

The fact that GNSS satellite orbits are determined in a global terrestrial reference frame makes ground receivers a versatile tool for measuring global plate tectonics and monitoring regional geodynamic processes. Albeit this application sounds simple as it only implies to continuously determine the position of a very slowly moving receiver antenna, it still requires some skills to filter the time series appropriately by removing disturbing effects, since the target is to measure very slow processes with drift rates in the range of a very few centimeters per year, often also at the sub-centimeter level. Nevertheless,

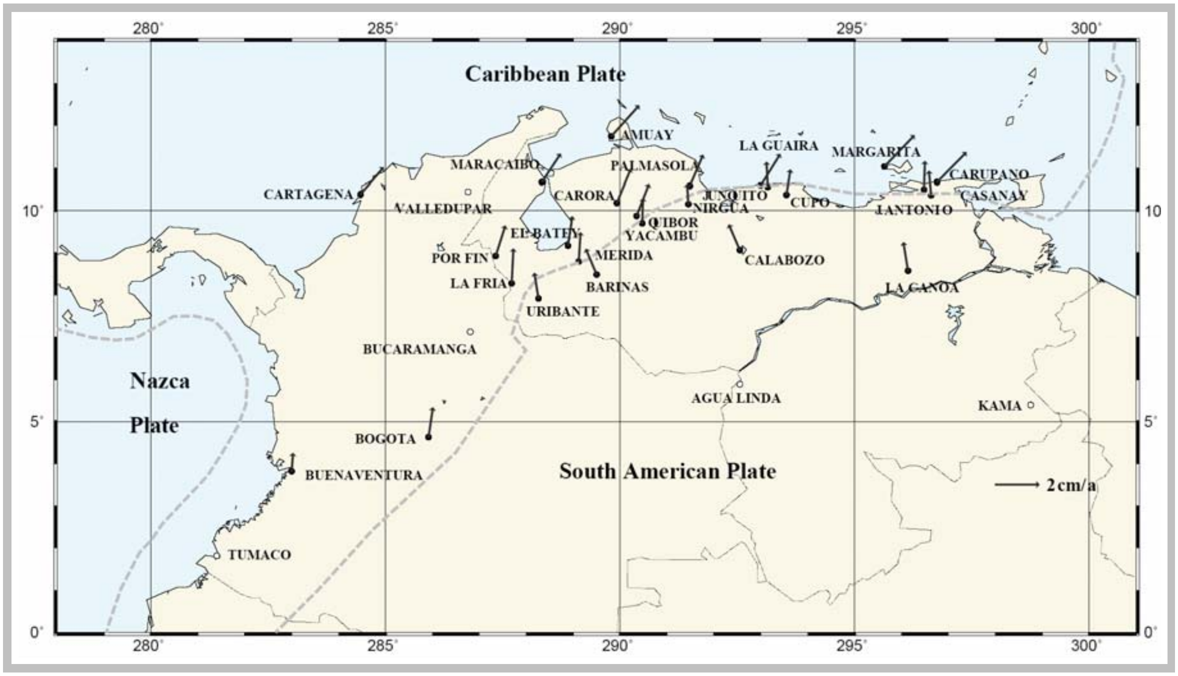


Figure 10-18: Regional geodynamics at the boundary of the South American and Caribbean plates revealed by GPS measurements (DGFI Annual Report 2001/2002, Deutsches Geodätisches Forschungsinstitut, München)

results for global plate tectonics obtained from GNSS measurements agree rather well with geophysical models, except for the plate boundary zones which are difficult to model. Figure 10-18 shows average horizontal motion rates in the boundary zone of the South African and Caribbean plates with typical rates between 1 and 2 cm per year.

10.4 Future Trends

With the advent of GPS many disciplines have revolutionized their measurement principles in positioning and navigation as well as in timing. In particular, satellite techniques are now replacing to a wide extent the traditional terrestrial methods. New applications come up every day. Water vapor estimation for the improvement of local weather models and occultation of the atmosphere are examples of byproducts never planned in the design of GPS.

Looking to the future, it seems that we are only at the beginning with respect to the applications of satellite navigation, which in many cases take advantage also of geoinformation and telecommunication in order to create value-added services. In this fast growing field it is difficult to predict long-term trends exceeding, say, five years. Nevertheless, the following can be expected:

- With the build-up of the European satellite navigation system Galileo to be completed around 2010 a new area in satellite positioning and navigation will start. Based on the frequency and signal structure and its bandwidths (all of them larger than those of GPS) *accuracy will increase* considerably (down to sub-millimeter level under ideal conditions). Real-time kinematic capabilities will become *more robust.* Integrity will be globally available at any time.
- Due to the *interoperability* agreement *between GPS and Galileo* the user will benefit in terms of availability of twice the number of satellites he is able to track with just the same receiver. In general, the user can observe two times eight to ten satellites and needs only four in order to determine a three-dimensional position). This *enormous redundancy* leads to more robustness and

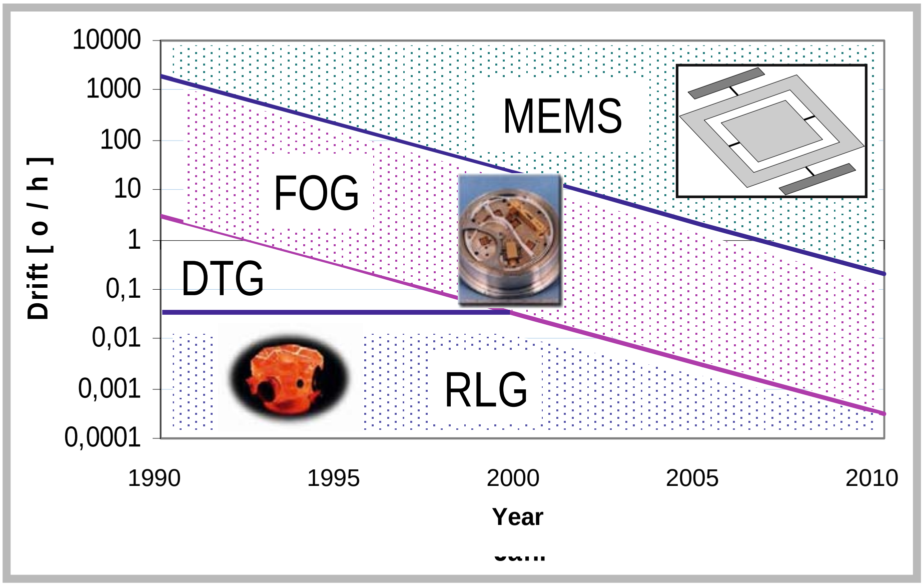


Figure 10-19: Drift development of inertial technology (Dry-tuned gyros (DTG), fibre-optics gyros FOG), ring-laser gy ros (RLG) and micro-electro-mechanical systems (MEMS)

to many new applications not yet really thought of. The *increased availability* will make it happen that satellite navigation can be used also in cities, urban canyons and areas with limited sky coverage.

- Satellite positioning and navigation will be possible also *indoors* using new developments in signal processing to increase the sensitivity of tracking weak signals and to mitigate multipath through new methods. Data sent via mobile terrestrial telecommunication will enable the receivers to acquire satellites in a second or less (so-called “Assisted Global Navigation Satellite System”).
- Satellite navigation receivers will be *integrated with various sensors* in the future, in order to overcome the deficiencies of satellite navigation in certain applications (interruption of signals, shadowing, autonomy, etc.).
- Considering complimentary properties, one prominent candidate is certainly the inertial navigation system (see e.g., Jekeli 2001). GNSS/INS integration can be carried out in different levels of closeness or tightness, both in the hardware and software, of the two sensors. Very important could be an ultra-tight coupling of a small INS (on a chip) with the tracking loops of a future GNSS receiver.
- Recent advances in micromachining of mechanical systems have led to the development and manufacture of very small, inexpensive inertial sensors (micro-electro-mechanical systems - MEMS, and micro-opto-electro-mechanical systems - MOEMS). Examples are safety and stability devices consisting of accelerometer(s) and/or gyro(s) in automobiles and other consumer products produced on a chip.
- Figure 10-19 outlines the expected drift behavior of different type of gyros like dry-tuned gyros (DTG), fiber-optics gyros FOG), ring-laser gyros (RLG) and MEMS devices over the next few years. Whereas no further development of ring-laser gyros is predicted and dynamically-tuned gyros will practically more or less vanish, a tremendous improvement of fiber-optical gyros can be foreseen (2005 drift 0.01...0.001^0/hr; 2010 drift 0.001...0.0001^0/hr). Also very interesting is that the MEMS technology may reach the 1^o/hr in 2008 to 2010.
- But also the integration of satellite navigation receivers with all kind of different sensors and techniques (odometer, UMTS/GSM, Bluetooth, WLAN, digital map, terrain-based information, etc.) will increase over the next years.

- Software receivers. Two decades have passed since the first commercial GPS receiver appeared on the market. Whereas the first ones were based on analog signal processing using large components demanding a lot of power, modern standard receivers are commonly based on ASICs (application-specific integrated circuits) for signal processing and fast microprocessors for position and application processing. ASICs guarantee on the one hand effective signal processing; however, every small change results in a costly-redesign of the system because it cannot be reprogrammed as easily as can a microprocessor.
- Considering the advances in the performance of microprocessors, all operations of an ordinary GNSS receiver can be carried out in future using a programmable microprocessor, making such a system highly flexible (changing just the source code). The software receiver consists then simply of the antenna, a front-end and A/D converter as well as a microprocessor. First PC-based versions are being developed which are able to process one frequency with 1 Hz data in real-time (Pany et al., 2004*)*. In the near future, more sophisticated multiple frequency solutions allowing also higher update rates will be possible depending on progress in microprocessor performance.
- Whereas it is expected that the first use of software receivers as defined above will concern a development platform for receiver manufacturers, one can also think of a very personalized receiver (integrated with personal application-oriented modules containing information and digital maps) in a decade from now (after 2010) when already the core receiver might be even available in public domain as a software module.

Acknowledgements

Some text and figures on Galileo provided by the European Commission in public domain are used (Business in Satellite Navigation. An overview of market applications. Brochure dated March 5, 2003). I acknowledge also the contribution of Dr Torben Schüler, Institute of Geodesy and Navigation, University FAF Munich on science applications.

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Space as a Laboratory

Overleaf image: Astronaut Ulrich Walter during the D-2 Spacelab mission (DLR)