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DIVAGATIONS ON THE APPROPRIATE SATELLITE SYSTEM FROM GNSS FOR AVIATION

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Abstract

American military satellite GPS system is an element of the global GNSS. It emits two codes: the precise and civil one. As late as in 2000, intentional interference that decreased precision of localization was introduced, allowing navigation accuracy of 20 m. GPS was made available to civil users, however, at their own responsibility. So, if we use GPS for our own goals, we must consider the errors that occur and their consequences. Nonetheless, commercial and operational needs determine the necessity of permanent access to satellite signal with appropriate consistency, accessibility, reliability and precision. Hence, natural and intentional errors are compensated for, using appropriate methods, based on a given activity.

Keywords: GPS, reliability, precision, consistency, availability, GNNS.
Type of the work: *General Review Paper*

1. INTRODUCTION

Dynamic scientific and technical development is the cause of common implementation of satellite techniques and technology, and of emergence of a new specialization – satellite navigation. This is a radionavigation specialization, science of navigating objects in Earth ecosphere and planning and using the necessary infrastructure, based on radio signals emitted by satellite systems, in order to provide accurate, reliable, dependable and safe obtaining the function of this movement target. Current satellite techniques and technologies are commonly used in different fields of activity (Fig. 1). It is worth noting that mobile devices with Android system allow using the following satellite navigation systems: American GPS NAVISTAR, Russian GLONASS, Chinese Beidou/Compass, European Galileo and Indian IRNSS.

However, the first satellite navigation system working in 1964-1996 was the American Transit-NNSS[1] used to determine the position by submarines (ships) with ballistic missiles of Polaris type. The system consisted of 10 satellites (including 5 spare ones) on low peri-polar orbits at the height of about 1100 km above the Earth surface. In 1967, the system was made available for civil use, and it served as the source of standard frequency, in sailing, as well as for hydrography and geodesy[2]. Unfortunately, the system

[1] NNSS – Navy Navigation Satellite System.

[2] In 1981, the author represented the Polish Air Force during scientific and research works of the navy on: "Analysis of positioning accuracy in the Transit system".

determined a 2D position and could not be used for spatial localization. Hence, based on the experience and eliminating the drawbacks of the system, in 1973, United States Air Force (USAF) initiated the "System 621B" project that would determine spatial position in 3D, which was integrated with other projects within the DNSS program[3] and has been known as GPS NAVISTAR since 1974[4]. In 1983, after flight KAL 007 of the Korean Airlines was shot above the Soviet Union Territory, a decision was made to give access to GPS NAVISTAR also for civil use, however only in 1995, the GPS system obtained its full operating capacity – FOC[5]. And in 2000, interference of ephemerids and fixes of satellite atomic clocks SA[6], allowing civil users to use satellite navigation at accuracy of 4 to 12 m (instead of 20-100 m). Since 2005, IIR-M satellites have been placed on the orbit, that allow the first-time use of the M signal for the military use, and L2C signal for civil forces.

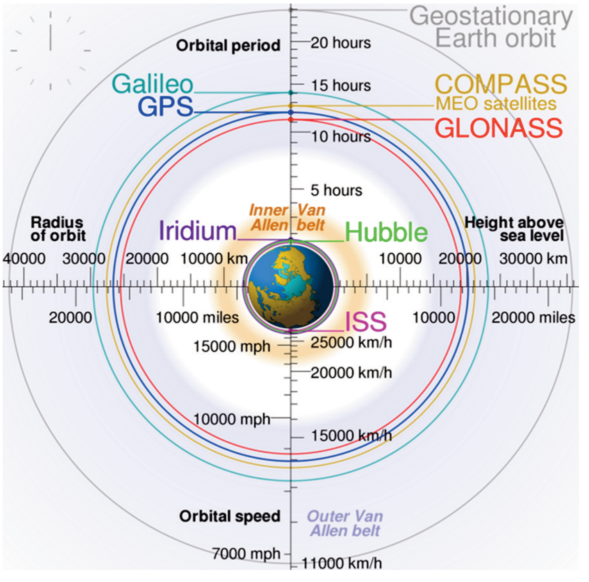

Fig. 1. Comparison of orbits of GPS, GLONASS, Compass and Galileo satellites with orbits of Iridium, Hubble Telescope and International Space Station satellites (source: Geo Swan, Wikimedia Commons, free media repository).

Since 1976, also the Russians own a military satellite navigation system GLONASS[7], which, similarly to GPS, is a stadiometric system[8] and it emits two types of signals: the military one and civil one. Also since 2000, the Chinese satellite navigation system Beidou (Ursa Major)/Compass exists, which will obtain a global range in 2020. Since 2006, the Indian satellite system IRNSS[9] is implemented as well.

[3] DNSS – Defense Navigation Satellite System.
[4] Global Positioning System – Navigation Signal Timing and Ranging.
[5] FOC – Full Operational Capability,
[6] SA – Selective Availability
[7] GLONASS – Russ. Globalnaja Nawigacionnaja Sputnikowaja Sistiema.
[8] The position is defined at the cross point of four spheres with radii calculated based on signal propagation time and with centers known from navigation a navigation message sent by the satellites.
[9] Indian Regional Navigational Satellite System.

Lack of trust in military satellite systems supervised by armed forces of the owner states that can be turned off or interfered at any time, as well as limitation of their precision for civil users were the reason why the European Space Agency[10] (ESA) initiated a Galileo program in 1999. This system of global satellite navigation is an alternative for the military systems, it is supervised and controlled by civil institutions. Full operational capacity of Galileo is planned in 2020. And the international IDS[11] agency controls and manages the data from Doppler satellite system DORIS[12], that measures precisely the parameters of satellite orbits, studies the level of seas and gravitational field, checks the coordinates of ground stations, scales for Earth reference systems, ionospheric information, precise ephemerids of satellites and parameters of Earth rotation. The data from DORIS system are used onboard altimetric and teledetection satellites.

Currently, military satellite navigation systems provide not only the precision signal, but also a standard one, for civil users. However, when we use it, it is at our own responsibility and we must remember about the possible errors and their consequences. The conducted analyses indicate that modern mobile phones have integrated satellite navigation modules that allow free use of GPS NAVSTAR, GLONASS, and Beidou/Compass systems Navigation requires appropriate maps and Internet data transmission with A-GPS function to shorten the time of the first localization. Nonetheless, commercial and operational needs determine the necessity of permanent access to satellite signal with appropriate consistency, accessibility, reliability and precision, which are not provided by the military satellite navigation systems. Hence, until Galileo system is operationally available, civil users must compensate natural and intentional signal disturbances to eliminate errors when using commercial satellite navigation. To obtain this, ancillary systems and appropriate methods of increasing accuracy are used: differential measurement (DGPS[13]), ancillary error correction systems (ABAS, SBAS, GBAS), ground permanent networks of reference stations, e.g. the European ASG-EUPOS[14] network.

2. FEATURES OF GNSS SYSTEM

The GNSS system operates in close connection to other techniques and technologies (Fig. 2), closely integrating with field geographic information systems (GIS) and international geographic information system (IGS). This results form the European co-modality policy[15], effective use of various transportation systems to obtain the optimal (in terms of economy, financing, service quality and environmental protection) and sustainable use of resources. Based on this all, intermodality and multimodality[16] appears in the developed trans-European transport network.

[10] ESA – European Space Agency.
[11] IDS – International Doris Service.
[12] DORIS – Doppler Orbitography and Radiopositioning Integrated by Satellite.
[13] DGPS – Differential Global Positioning System.
[14] ASG-EUPOS – Aktywna Sieć Geodezyjna (Active Geodesy Network) EUropean POSition Determination System.
[15] COM(2006) 336, Communicate of the Committee to the Council, European Parliament, European Economical and Social Committee and Region's Committee, Logistics of goods transportation in Europe – the key for sustainable mobility, Brussels, 28.6.2006.
[16] P. T. Nowakowski, Multimodalność transportu publicznego w Filadelfi (Multimodality of public transportation in Philadelphia), Komunikacja Publiczna No. 4/2015-2016. 36-42.

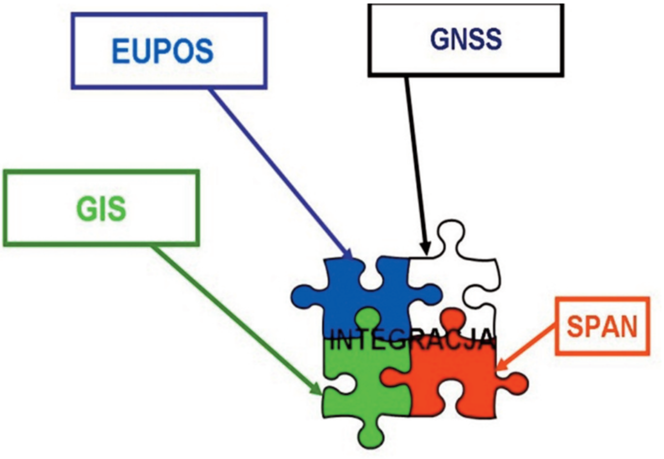

Fig. 2. Integration of systems for aviation use: GNSS, SPAN, EUPOS, GIS.

Implementation of global transport and communication transformation, as well as European multimodality require interdisciplinary view and close cooperation of the following systems:

EUPOS (Fig. 3) – European network of ground, multifunctional permanent reference stations of precise satellite positioning (ASG-EUPOS), which is a part of the international IGS network. In Poland, the correct functioning is ensured by the Main Office of Geodesy and Cartography; it provides:

- ✓ functioning of permanent, multifunctional, differential reference station DGNNS;
- ✓ precise determination of coordinates of ground stations (ETRS' 89 and conventional geodesy reference systems);
- ✓ use of standards for satellite systems of operation systems (GPS, GLONASS, and soon Galileo)
- ✓ possibility to use the following services:

Real time:

NAWGEO – measurement using the kinetic method (**RTK, RTN**), emitted correction RTCM, RTK, VRS, FKP data in real time from the chosen or generated virtual reference station, allow measurements and navigation with precision below 0.03m horizontally and 0.05 m vertically;
KODGIS – measurement using kinetic method (DGNSS), emitted correction RTCM data in real time, from the chosen reference station, they allow measurement and navigation with precision of 0.25 m);
NAWGIS – measurement using kinetic method (DGNSS), emitted correction RTCM data in real time, from the chosen reference station, they allow measurement and navigation with precision of 3 m);

Post-processing:

POZGEO – measurement using static method, and phase observations from single- and dual-frequency receivers converted to the defined format of observation data are used for calculation;
POZGEO D – measurement using static and kinetic method; provides observational data for independent calculation and allows obtaining precision at the level of 0.1 m for L1 receivers and 0.01 m for L1/L2 receivers. After the measurement and measurement sessions of the reference stations are completed, the user can download observation files for chosen reference stations and process the data individually.

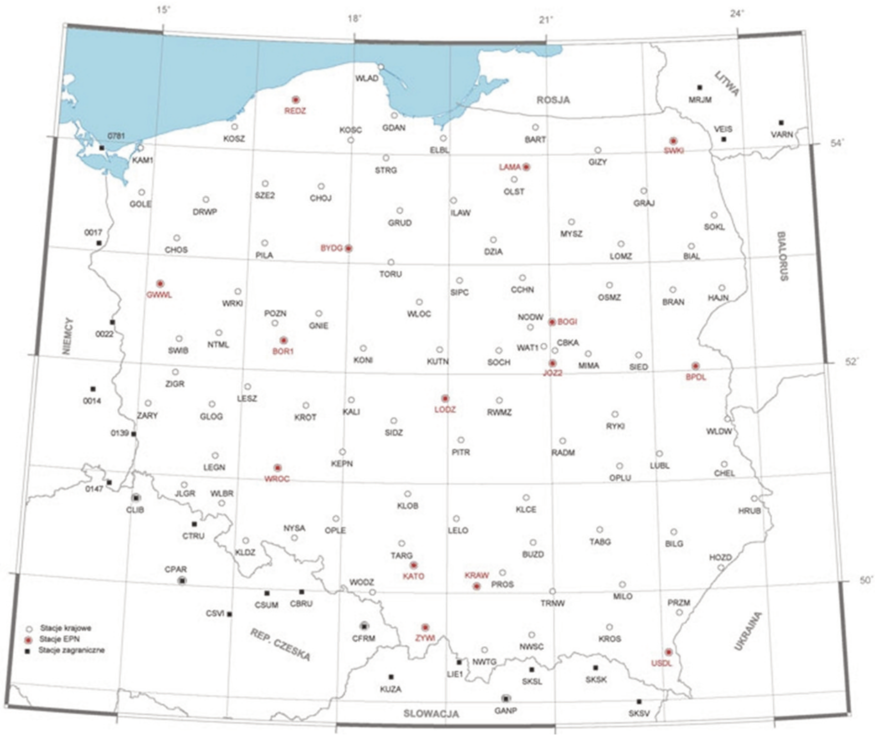

Fig. 3. Distribution of ASG EUPOS system (source: http://www.asgeupos.pl); some stations are additionally equipped with: GLO (GPS/GLONASS), MET (meteorological measuring sets), EPN (European), IGS (international).

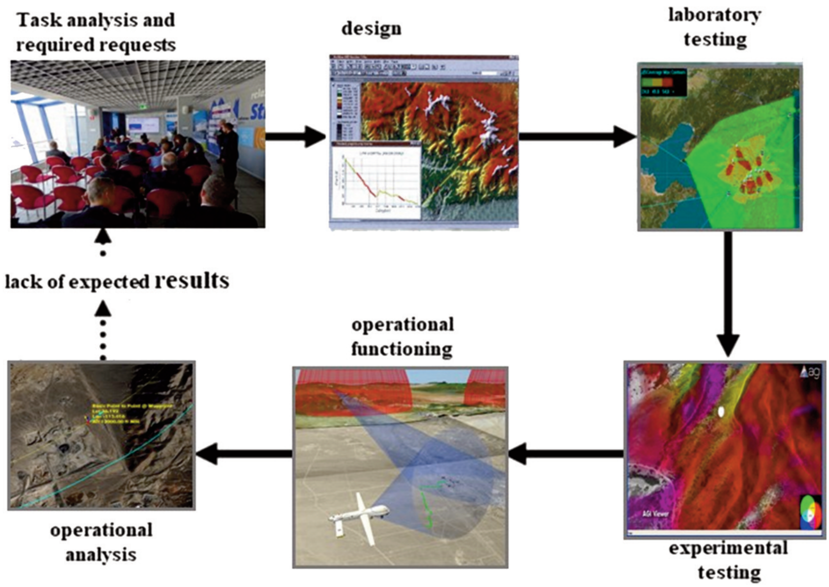

Fig. 4. Algorithm to determine the procedure to perform an aviation task from analysis of the task to operational application (based on AGI).

Geographic Information Systems (GIS) – broad application for automatic generation of numeric model of terrain (NMT) and orthomap creation. The user can collect data, manage data and apply them at their discretion. The photogrametric process (integration with teledetection, GIS) covers three steps: image acquisition, its photogrametric processing and product development. The conducted research allowed to develop and test algorithm functioning based on processing of geodata, interpretation and spatial analysis as well as terrain visualization (Fig. 4). Implementation of satellite techniques and technologies in aviation requires the use of numeric terrain model and the measurement problems result from airport localization in urbanized areas, the necessity to perform measurement of many point at the airport an within a strictly defined radius around it, as well as objects and aviation obstacles that are difficult to measure.

SPAN – cooperation of satellite navigation GNSS receivers with autonomous inertial INS, to allow availability, continuity, accuracy and reliability of spacial localization, especially during temporary loss of satellite signals (Table 1). The necessity of such cooperation was confirmed by the first-in-Poland test flights around Mielec airport in 2007 (Fig. 5). Upon satellite monitoring, multifrequency GNSS receivers are prone to interference and then they are complemented by autonomous inertial systems (AHRS, IMU) that determine orientation and position based on acceleration and angular velocity. They are used for stabilization. Currently, three main inertial systems are determined:

a) **IMU** (**Inertial Measurement Unit**) – triple axis gyroscope and accelerometer allow precise determination of an object in two axes. It is, however, prone to drift, as the azimuth measurement is based on counting;
b) **AHRS** (**Attitude and Heading Reference System**) is IMU complemented with a magnetometer that measures Earth magnetic field, allows precise determination of object orientation in three axes;
c) **INS** (**Inertial Navigation System**) – inertial navigation system based on IMU data; it allows calculation of position, velocity and location (roll, pitch and azimuth). In aviation, INS cooperates with GNSS, as these two navigation techniques enhance mutually and increase each other's possibilities. Stable relative position of autonomous INS is indicated when the GNSS signal is degraded or not available.

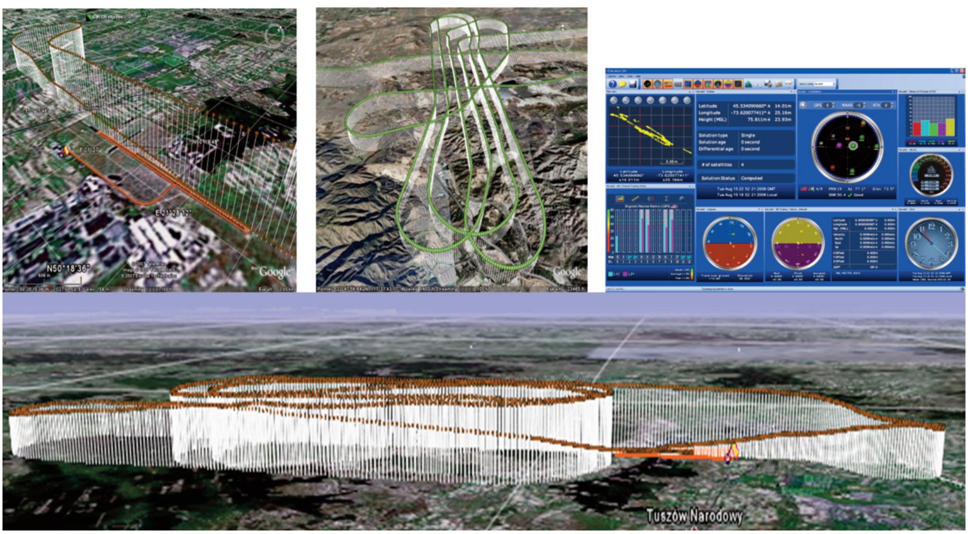

Fig. 5. Imaging of SPAN tests around Mielec airport (taxiing, take-off, making turns, approaching and landing): imaging of the whole procedure, measurement panel, vertical section.

Table 1. Features and operational characteristics of GNSS and INS systems.

Feature	GNSS system operational characteristic	INS system operational characteristic
independence	requires external GNSS signal	does not require any external signals
precision of vertical coordinate	a few times worse than that of the horizontal coordinate	a few times better than that of the horizontal coordinate
accuracy dynamics	the accuracy can vary and depends on the number of traced satellites, geometry and positioning mode	stable accuracy, however, it gradually degrades over time
result characteristics	can provide absolute coordinates	provides accurate, but relative coordinates
direction data	movement direction data only as a function of velocity (azimuth and pitch)	provides complete direction data in three dimensions
positioning frequency	positioning frequency max 20 Hz	large operational frequency up to 200 Hz

GNSS (Global Navigation Satellite System) – this is not a uniform system, as currently, this name covers (Fig. 6):

a) standard satellite systems:

- **American military GPS NAVSTAR (Global Positioning System NAVigation Signal Timing and Ranging)** – full operational capacity since 1995, maintained and managed by the U.S. Department of Defense. Global satellite navigation system composed of 3 segments: space[17], ground (control and monitoring stations), user (receivers). GPS system includes: almanac (system data that speed up the acquisition process) and ephemerids (precise orbital elements of the satellite that is sending the message, necessary to determine time and position). Signal structure for this system: L1 (f_1 = 1575.42 MHz), L2 (f_2 = 1227.60 MHz), L5 (f_5 = 1176.45 MHz). The following signal coding methods are used: C/A, P used along with Y code (P/Y), L2C, M, codes transmitted at the frequency of L5 – C5, L1C. Each satellite signal is superimposed with information in a form of satellite message: NAV (L1), CNAV (L2, L5), MNAV, CNAV-2 (L1C). A significant element of the system is identification of individual satellite signals in a receiver with pseudo-random noise[18], that allows using the signal to transmit coded military messages. The functioning satellites of IIR, IIR-M block equipped with rubidium clocks or hydrogen masers[19], laser mirrors can function for 14 days without contact with control stations; they are able to transmit signal intentionally degraded by SA and AS, and to mutually measure distance and communication. The basic reference system based on WGS-84 ellipsoid. 1 second is a unit of GPST time that is coordinated with international atomic time (TAI) and describes as: TAI – GPST = 19 s + C0[20].

[17] 24 satellites plus supplemental ones (a total of 32 satellites), 6 orbits with a tilt of 55° with relation to the equator plane; orbit height 26.560 km, time of circulation: 11 hours 58 mins; each satellite has got atomic clocks.

[18] PRN – Pseudo-Random-Noise.

[19] Increased precision of time determination from 10-7 to 10-10 s/day.

[20] C0 is a variable correction of the order of 10 ns due to potential differences of atomic clocks in these systems.

- **Russian military GLONASS (Russ.** РГЛОНАСС – Глобальная навигационная спутниковая система**)** – put into operation in 1995; full operational capacity since 2015; maintained and managed by the Space Army of the Russian Federation. Global satellite navigation system composed of 3 segments: space[21], ground (control and monitoring stations), user (receivers). The GLONASS signal contains: almanac (system data that speed up the acquisition process) and ephemerids (precise orbital elements of the satellite that is sending the message, necessary to determine time and position). All GLONASS satellites transmit the same code, but each satellite transmits the signal at a different frequency L1 (f_{L1} = 1602 MHz ± k[22]), L2. Frequencies L1 and L2 are elated as f_{L1} / f_{L2} = 9/7, and by measuring at the two frequencies, ionospheric refraction is eliminated. Time signals are referenced to UTC[23]$_{SU}$. Satellite coordinates are provided in the PZ-90.11[24] coordinate system. The signal format "INFO GLONASS Superframe" contains: satellite data, elements of perturbation acceleration due to non-central Earth gravitational field and Moon influence, correction of satellite clock to GLONASS time, calendar (date), and satellite ID number. It is significant that the system is not using any signal interferences, it emits signals for military and civil users via the satellites.
- Chinese military **BeiDou/ Compass** – it has been working since 2003, full operational capacity will be achieved in 2020, it is maintained and managed by the Chinese armed forces. Global satellite navigation system composed of 3 segments: space[25], ground (control and monitoring stations), user (receivers). The satellite signal is transmitted at frequencies B1 (1575.42 MHz), corresponding to civil L1 (GPS NAVSTAR) and E1 (Galileo), generates navigational message (almanac, ephemerids, corrections). It emits signals for military and civil users. Additionally, it allows sending SMS (Short Message Service) messages among the system users.
- **Indian military system – IRNSS (Indian Regional Navigational Satellite System)** – full operational capacity since 2016, maintained and managed by the Indian government and armed forces. Global satellite navigation system composed of 3 segments: space[26], ground (control and monitoring stations), user (receivers). The system emits two signals: SPS[27] (civil one) and PS[28] (coded one). Both signals are transmitted over two frequencies: L5 (1164-1189 MHz) and S (2483.5, 2500, 2492.028 MHz).
- **Civil system – Galileo Galileo** – the first civil system initiated in 2016, with planned full operational capacity in 2020; maintained and supervised by ESA[29]; is an alternative and competitor for the military systems. Global satellite navigation system composed of 3 segments: space[30], ground (control and monitoring stations), user (receivers). The satellites transmit the signals in three frequency bands and offer the following services:
  - ✓ **OS (Open Service)** – free, accuracy 4 to 15 m horizontally and 8 to 35 m vertically;

[21] 24 satellites in 3 orbits (8 satellites on each one of them) with a tilt of 64.8° with relation to the equator plane; orbit height 19.100 km, time of circulation: 11 hours 15 mins; each satellite has got atomic clocks.

[22] k value can be from -7 to +6 for satellites launched after 2005.

[23] UTCSU – Universal Coordinated Time in Russia.

[24] PZ-90.11 (*Parametry Zemli* 1990.11), in agreement with international ITRF 2000 system.

[25] 35 satellites (27 at a medium Earth orbit (MEO), 5 at a geostationary orbit (GEO) and 3 at geosynchronous orbit (IGSO). For MEO and IGSO satellites, the tilt is 55°. Orbit height: 21.500 km (MEA) and 35.786 km (IGSO).

[26] 7 satellites (3 at a geostationary orbit and 4 at a geosynchronous orbit 29° with relation to the equator plane; orbit height is 36.000 km above Earth.

[27] SPS – Standard Positioning Service.

[28] PS – Precision Service.

[29] ESA – European Space Agency.

[30] 30 satellites (24 plus 6 spare ones) at 3 orbits with a tilt of 56° with respect to the equator plane; orbit height 23.222 km

- ✓ **SoL (Safety of Life)** – expansion of OS with warnings about loss of data reliability – information for the user about worsening of accuracy of the determined position (operational and commercial application);
- ✓ **CS (Commercial Service)** – accuracy 0.8 m horizontally and 1 m vertically, and option to send messages from ground stations to the users;
- ✓ **PRS (Public Regulated Service)** – dedicated to chosen users who require high accuracy and reliability of data necessary to determine position and time and related to national security;
- ✓ **SAR (Search and Rescue)** – collecting signals of calling for help along with identification of localization and submitting the information to the rescue teams. Integrated with the functioning global marine and aviation rescue system Cospas-Sarsat.

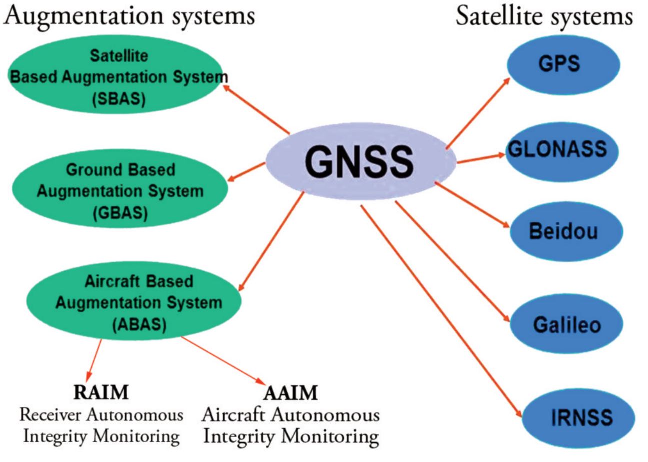

Fig. 6. Components of GNSS.

b) supplementary systems – allow operational and commercial use of military satellite systems for civil purposes, providing the required reliability, accuracy, availability, consistency of the signal. Depending on localization of the supplementary system, overlay augmentations can be defined.

- ✓ **ABAS** – a technique based on RAIM (Receiver Autonomous Integrity Monitoring) of GNSS receiver; monitoring of satellite signal consistency and alerting in case of loss of the required navigation accuracy due to erroneous satellite indications. RAIM uses the FDE[31] algorithm, which detects erroneous indications of the satellites, excludes them from calculations and provides safe navigation continuation;
- ✓ **GBAS** – ground monitoring stations verify the satellite signals, improve their accuracy by calculation corrections, and transmit them via ground stations at VHF-VDB band.
- ✓ **SBAS** – ground monitoring stations verify the satellite signals, improve their accuracy by calculation corrections, and transmit them via geostationary satellite to the user. It must be highlighted that this is a dynamically developing group of compatible systems of satellite support (Fig. 7), consisting of e.g.: the European EGNOS, American WAAS (Wide Area Augmentation System), Japanese MSAS (Multifunctional Satellite Based Augmentation System), Russian SDCM (System of Differential Correction and Monitoring), Canadian CWAAS (Canadian WAAS), Chinese SNAS

[31] FDE – Fault Detection & Exclusion.

(Satellite Navigation Augmentation System), Indian GAGAN (GPS and Geo-Augmented Navigation System), South Central American and Carribean SACCSA (Solucin de Aumentación para Caribe, Centro y Sudamérica), African Indian AFI (Africa and Indian Ocean), Australian GRAS, Japanese QZSS (Quasi-Zenith Satellite System) or Korean K-SBAS[32]. Although these are regional systems, they fulfill the international Minimum Operational Performance Standards (MOPS), which means that onboard user receivers can use the signals independently of the system that emits them.

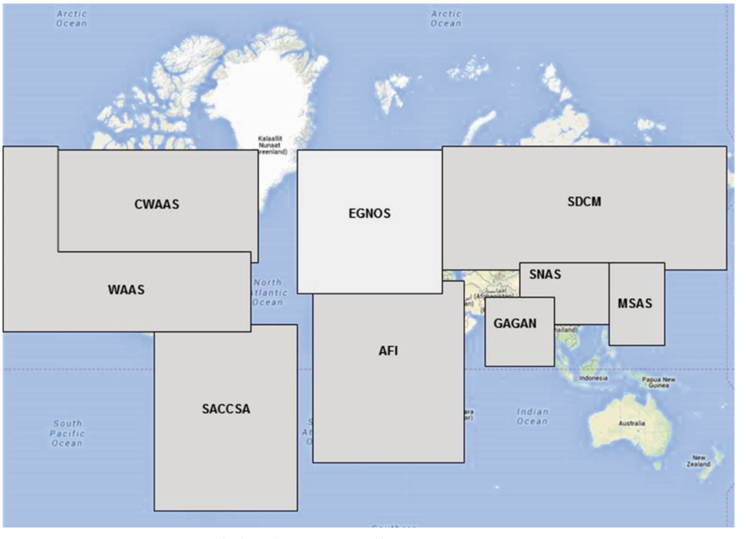

Fig. 7. Functioning and developing satellite augmentation systems SBAS.

3. FUNCTIONING OF SATELLITE NAVIGATION SYSTEMS

Determination of position is based on measurement of signal propagation time (code measurement) and phase shift (phase measurement) of the signal transmitted by a satellite moving on a known orbit. Based on a known velocity of electromagnetic wave and the precise time when signal was sent, distance between the receiver and the satellites is calculated. Then, by performing spacial linear cut-back, the receiver can calculate the geographical position (longitude and latitude, and elliptic altitude). Hence upon determination of spatial position, independent receipt of signal from at least four satellites is necessary, as the receiver calculates 4 variables: three pseudo-distances form the satellites and time deviations[33].

It is known that measurement of distance from satellite is performed based on determination of differences between indications of the clock of the transmitting satellite and the clock receiving the signal. This means that time of sending the signal from the satellite is determined based on one clock and the receipt time based on a second clock. Time synchronization in the system is a very important element and it is the main goal of the control segment of the GNSS system. Of course, if satellite clocks were precisely synchronized with the receiver clocks, then distance measurements, after consideration of propagation correction t_A, would not be burdened by this error; however, this is technically not possible.

[32] http://www.esa.int/Our_Activities/Navigation/ESA_guides_global_satnav_augmentation_gathering.

[33] Differences between cheap and not-precise-enough quartz standard placed in the receiver and the precise atomic clock in the satellite.

It is known that stability of satellite atomic time standards is 1×10^{-14} and in receivers with quartz generators in short time spans it is 1×10^{-12}. It is also known that error in synchronization of satellite clock time and receiver clock time of 1μs causes distance error of 300 m. Physically, high time standard synchronization cannot be achieved, hence the GNSS system uses software solutions that ensure accuracy of 1 nanosecond (distance error of 0.3 m)[34].

The satellite GNSS measurement is based on determination of distance between the user receiver and the satellite, and it can be obtained using two methods:

a) Code method (pseudo-distance measurement) – measurement of propagation of the emitted satellite signal modulated with a special code and its arrival at the receiving antenna is determined as: $D = c \cdot t$

c – velocity of electromagnetic wave propagation in the given medium,
t – the determined propagation time.

It is difficult to accurately determine the c velocity, as the signal passes through a non-homogeneous medium.

b) Phase method (phase measurement) – distance measurement is based on determination of the phase of a signal reaching the receiving antenna. In this case, distance determination requires knowledge of number of phase cycles (N) of the electromagnetic wave on its path from the emitter to the receiver and it is determined as: $D = (N + \varphi) \cdot \Delta D$

N – number of full phase cycles,
ΔD – wavelength of the electromagnetic wave,
N – number of full phase cycles,
φ – measured phase of the incoming signal.

Commonly, measurement at two or more bound frequencies is used to decrease the medium influence on the determined distance from the satellites. This method allows obtaining accuracy of 2-3 cm, however one disadvantage is the necessity to determine phase uncertainty N (initialization of the receiver).

In the GNSS system, the measured "pseudodistances" contain the following errors due to: propagation of radio waves in the ionosphere and troposphere Ct_A, difference in indications of the satellite clock and the receiver clock Ct_U, difference of indications between the satellite clock and the system time CtS. The measured pseudodistance contains: real distance, distance correction due to refraction and error of the receiver clock (Fig. 8).

Considering the above, pseudodistance relation is described with a formula considering: the time measured by the receiver, the time known after the signal is decoded, correction determined by the receiver, correction transmitted by the satellite in the satellite message. The ephemerids error[35] is not considered, as this value is prognozed. The value of receiver clock correction is unknown and hence it must be determined along with coordinates of the user position as an additional variable. The minimum number pf measured pseudodistances must be higher by at least one than the number of user position coordinates[36]. This means that the measured distances to the satellite alway bear the same constant error of $c\Delta t_u$. It turns out that the three measured pseudodistances with values determined in the user receiver do not cross at one point. Hence, if we consider that this error is due to the receiver clock, each line must

[34] The synchronization level is ensured by the network of control stations that permanently monitor the satellite clocks and introduce corrections as needed. And upon position determination, correction of the receiver clock with respect to the satellite is determined.

[35] Satellite location at the moment of measurement.

[36] STANAG 4294.

be shifted by the same value of $c\Delta t_u$. As a result, the common crossing point is obtained (the user position). This means that after determination of the user position, value of receiver clock error is always determined apart from the position (Fig. 9).

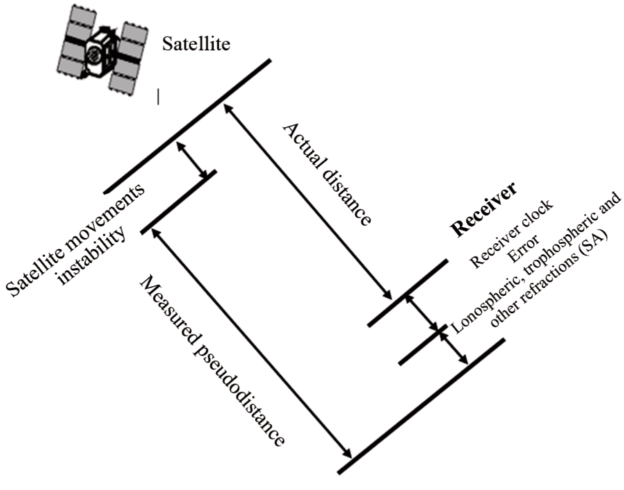

Fig. 8. Scheme of parameters that are important upon measurement of satellite-receiver distance.

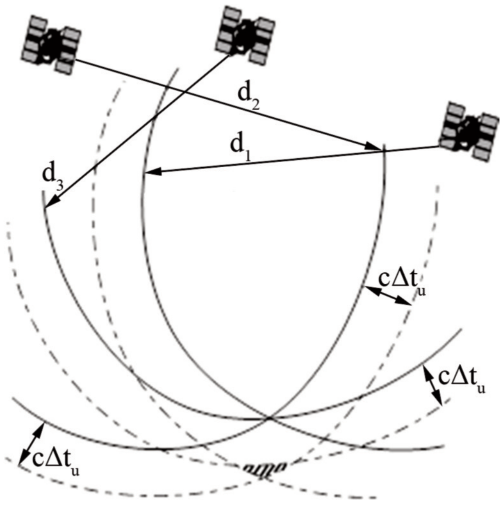

Fig. 9. Determination of coordinates and the determined user clock correction.

4. SUMMARY

The material was prepared base on own experiences and the results obtained from the following projects: EGNOS Introduction in European Eastern Region, HEDGE, SHERPA, PAŻP - PR 42 NPA-GNSS. Each of them was completed with operational and commercial implementations of satellite techniques for the needs of transportation. Results from research showed that standard civil level of military signals from GNSS satellite systems does not ensure safe operational or economic activity although it is commonly available. It does not ensure permanent accuracy, continuity, availability and reliability of the satellite signal that is necessary for the user. And each user of satellite navigation system, who wants to properly use the receiver, should know the following, basic terms that define the measurement results:

Dilution of Precision (DOP) – a factor that characterizes the geometric accuracy of GNSS satellite constellation at a given place. It is assumed that the satellite constellation can be very good (DOP 1–3), acceptable (DOP 3–6) or bad (DOP >6). A few kinds of this factor can be defined for determination of: GDOP (geometry), PDOP (spatial coordinates), HDOP (horizontal coordinates), VDOP (vertical coordinate), TDOP (time).

Signal-to-Noise Ratio (SNR) – ratio of strength of satellite signal reaching the GNSS receiver to noise. High SNR indicates lack or minor influence of external interferences on the satellite signal – good measurement conditions.

Signal multipath – the satellite signal from the satellite to the receiver can be reflected. In such case, the receiver receives two signals (the direct and reflected one) which can result in erroneous measurement of distance.

Based on the research, tests and experiments, the commonly used military satellite systems made available to the civil users cannot be used directly for operational and commercial activity. Currently, a popular method to increase accuracy is to use differential calculation (DGNSS[37]). It is based on the use of base (reference) station, i.e. receiver placed in an accurately determined place, which continuously determines the difference corrections for individual satellites and transmits them in RTCM, CMR or other format via satellite link, VHF, GPRS/WLAN directly to the user receiver. This method allows elimination of the satellite clock error, ephemerids error, selective availability (currently disabled)m ionospheric delay, and tropospheric delay. However, it does not eliminate the own noise of the receiver and the effect of satellite signal multipath. It must be highlighted, that for operational and commercial use of DGNSS method, standard requirements for different navigation types were determined: for railroad, road, air, marine transportation, and for other applications (Tables 2, 3, 4, 5, 6). Similar activity is seen from augmentation system mentioned in the material (ABAS, SBAS, GBAS), and local reference stations (IGS, ASG EUPOS).

DEFINITION STAGE	DEVELOPMENT STAGE	PLACEMENT STAGE
Development of central plan to manage aviation (determination of technological stages, priorities, schedules)	Research and development, and validation activities with respect to new technologies and procedures that are the basis of new-generation systems	Large-scale production and implementation of new technologies and procedures
2005-2007	2008-2014	2015-2020
SESAR CONSORTIUM 60 million Euro	COMMON UNDERTAKINGS SESAR 2.1 billion Euro	Aviation industry 30 billion Euro

Fig. 10. SESAR project and its stages.

[37] DGNSS – Differential Global Navigation Satellite System.

In Europe, until full operational capability of the civil Galileo satellite system is obtained, the satellite augmentation system EGNOS is preferred for commercial purposes, and financing is provided to this aim within the scope of SESAR program (Fig. 10). By signing the A-36 ICAO resolution in 2007, (A-37, updated in 2010), Poland obliged to implement the PBN (Performance Based Navigation) strategy in the air transportation. It became necessary to use the European satellite augmentation system EGNOS; European service provider – ESSP (European Satellite Services Provider) assigned by the European GNSS Agency (EGA) is responsible for functioning of this system until 2021. To fulfill its commitments and introduce the RNAV GNSS approach procedures on the Polish airport, Polish Air Navigation Services Agency (PANSA) signed an EWA (EGNOS Working Agreement) with ESSP in 2013. Hence, a formal basis for implementation of EGNOS system in Poland has appeared. It was also necessary to enter an agreement with the Head Office of Land Surveying and Cartography that is responsible for functioning of ASG EUPOS system. At the same time scientific and research works are undertaken within the scope of developing the civil global Galileo satellite system. It is interesting to know that as early as in 1996, Polish satellite receiver NAVI NT 04 (Fig. 11) was available and was testes in Silesian Region; the author tested it in the Polish air force.

Table 2. Required accuracy, time to alarm, availability and coverage of DGPS for the needs of railroad transport.

Use in railway system	Accuracy (2σ)	Time to alarm (2)	Availabilty (%)	Coverage area
Train localization tracking	10–30 m	5	99.7	Country area
Determination of speed	±1 km/h for v<20 km/h ±5% for v>20 km/h	5	99.7	Country area
Managing trains	1 m	<5	100	Country area
Warning about traffic at rail/road crossing	1 m	<5	100	Country area

Table 3. Required accuracy, time to alarm, availability and coverage of DGPS for the needs of road transport.

Use in road transport	Accuracy (2σ)	Time to alarm (s)	Availability (%)	Coverage area
Navigation and managing traffic	5-20 m	1–15	99.7	Country area
Alarming about traffic accidents	5-30 m	1–15	99.7	Country area
Transport management	25–1500 m	1–15	99.7	Country area
Automatic notification about coach stopping	5-30 m	1–15	99.7	Country area
Driving and controlling vehicles	30–50 m	1–15	99.7	Country area
Avoiding collisions: critical situations	5 m	1–15	99.7	Collision area
Collecting data on accidents	30 m	1–15	99.7	Country area
Infrastructure management	10 m	1–15	99.7	Country area
Avoiding collisions: controlling	1 m	1–15	99.7	Collision area

Table 4. Required accuracy, time to alarm, availability and coverage of DGPS for the needs of air transport.

Use in air transport	Accuracy (2σ)	Time to alarm (s)	Availability (%)	Coverage area
Transoceanic flights	23 km (12.6 Mn)	30	99.977	8,400–12,200 m (27,500–40,000 ft)
National flights	1000 m	10	99.977	150–18,300 m (500–60,000 ft)
Terminals	500 m	10	99.977	150–5,500 m (500–18,000 ft)
Approaching and landing: non-precise	100 m	10	99.977	75–900 m (250–3,000 ft)
Approaching and landing: category I	Horizontal: 17.1 m Vertical 1.7 m	6	99.999	30–900 m (100–3,000 ft)
Approaching and landing: category II	Horizontal: 5.2 m Vertical 1.7 m	2	99.999	15–900 m (50–3,000 ft)
Approaching and landing: category III	Horizontal: 4.1 m Vertical 0.6 m	2	99.999	0–900 m (0–3,000 ft)

Table 5. Required accuracy, time to alarm, availability and coverage of DGPS for the needs of marine transport.

Marine use	Accuracy (2σ)	Time to alarm (s)	Availability (%)	Coverage area
Shipping in harbors and mooring: large ships and tugboats	8–20 m	6–10	99.7	Ports, port approach
Shipping in harbors and mooring: small ships	8–20 m	6–10	99.9	Ports, port approach
Shipping in harbors and mooring: testing resources	1–3 m	5	99.0	Ports, port approach
Coastal shipping: all ships	460 m (0.25 Mn)	Not defined	99.7	Coastal waters
Coastal shipping: recreation boats and other small ships	460–3,700 m (0.25–2 Mn)	Not defined	99.0	Coastal waters
Ocean shipping: navigation safety	3,700–7,400 m (2–4 Mn)	Not defined	99.0	World area
Ocean shipping: all vessels	1,800–3,700 m (1–2 Mn)	Not defined	99.0	World area

Table 6. Required accuracy, time to alarm, availability and coverage of DGPS for the needs of other navigational applications.

Use	Accuracy (2σ)	Time to alarm (s)	Availability (%)	Coverage area
Remote control (3D)	Under study	Under study	Under study	World area
Searching and rescue	10 m	Not defined	Not defined	Country area
Area observation	1–5 m	Minutes – hours	95–99	Country to world area
Photogrammetry	2–5 cm	Minutes	Not defined	Country area
Geodesic observations	Horizontal: 2–40 cm Vertical: 1 cm	Hours (data after processing)	99	Places in country area
Border observation	Horizontal: 0.02–1 m Vertical: none	Hours (data after processing)	99	Places in country area

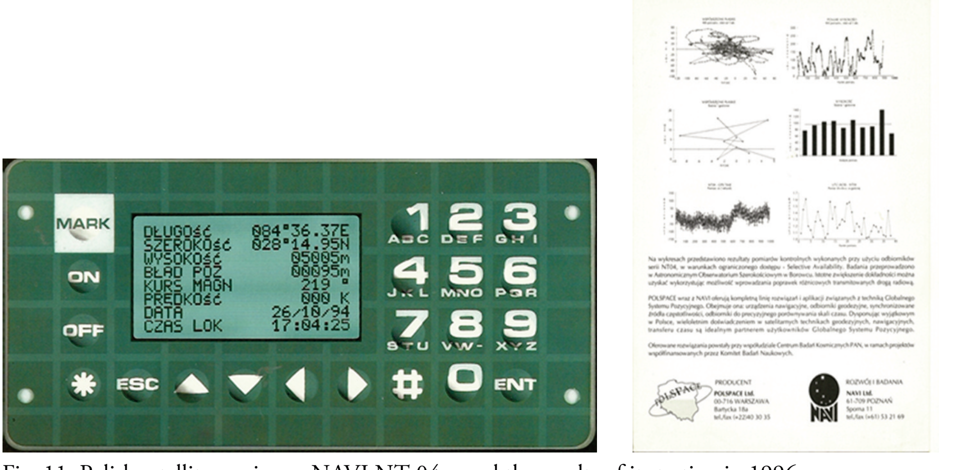

Fig. 11. Polish satellite receiver – NAVI NT 04 – and the results of its testing in 1996.

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NOMENCLATURE

ASG-EUPOS – Aktywna Sieć Geodezyjna EUropean POSition Determination System
DGPS – Differential Global Positioning System
DNSS – Defense Navigation Satellite System
DORIS – Doppler Orbitography and Radiopositioning Integrated by Satellite
EASA – European Space Agency)
ESA – European Space Agency
FDE – Fault Detection & Exclusion
FOC – Full Operational Capability
Global Positioning System – Navigation Signal Timing and Ranging
GLONASS – (ros. ГЛОНАСС, Глобальная навигационная спутниковая система) Globalnaja Nawigacionnaja Sputnikowaja Sistiema
IDS – International Doris Service
NNSS – Navy Navigation Satellite System
PRN – Pseudo-Random-Noise
PS – Precision Service
PZ-90.11 – a geodetic datum defined for use in the GLONASS system (short for Parametry Zemli 1990.11)
SA – Selective Availability
SPS – Standard Positioning Service
UTCSU – Russia Coordinated Universal Time

DYWAGACJE NA TEMAT ODPOWIEDNIEGO Z GNSS SYSTEMU SATELITARNEGO DLA LOTNICTWA

Abstrakt

Amerykański, militarny system satelitarny GPS stanowi element globalnego GNSS. Emituje dwa kody: precyzyjny i cywilny. Dopiero w 2000 r. wyłączono celowe zakłócanie zmniejszające precyzję wyznaczania pozycji, pozwalające uzyskać dokładność nawigacji do 20 m. GPS został udostępniony użytkownikom cywilnym, ale na ich własną odpowiedzialność. Toteż o ile stosujemy GPS dla swoich potrzeb to musimy liczyć się z powstałymi błędami i wynikającymi z nich konsekwencjami. Jednak potrzeby komercyjne, operacyjne determinują konieczność permanentnego dostępu do sygnału satelitarnego, charakteryzującego się odpowiednią: ciągłością, dostępnością, wiarygodnością, dokładnością. W związku z tym naturalne i celowe błędy kompensuje się stosując odpowiednie metody, w zależności od prowadzonej działalności.

Słowa kluczowe: GPS, wiarygodność, dokładność, ciągłość, dostępność, GNSS.