Relativity in Engineering

Characteristics and performance of global positioning systems

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***Abstract* - The GPS (Global Positioning System) has been, since its development in the 70s, the reference for GNSS systems. This system initially arose with military motivation, having been made available for civilian use only later, in the second half of the 90s. Since 1998, the European Union demonstrated its willingness to break the dependence on the U.S. GPS system and announced the development of a global positioning system with entirely civil character - GALILEO. The GNSS systems, due to the speed and height of their satellites, suffer relativistic effects which cause a deviation of the rate of vibration of embedded clocks in satellites compared to clocks located on the earth, or in its neighborhood. If not taken into account, those effects would make the system completely useless. They are explained by the Theories of Relativity - General and Special – of Albert Einstein. The goal of this report is to compare the two systems (GPS - Galileo) and the level of their physical skills and techniques, in particular their segments, available services and signal. An analysis of the errors, due to relativistic effects and the corrections to be made in both systems will also be carried out. Supported on Einstein's theories of Special and General relativity it was possible to determine the corrections to be made on the clocks due to relativistic effects, obtaining a correction of 39µs/day and 41µs/day to GPS and GALILEO, respectively.**

***Index Terms* - GPS, GALILEO, GNSS, Relativistic effects**

I. Introduction

The GNSS (Global Navigation Satellite System), especially since the opening of the GPS to the civilian public, has been experiencing a tremendous development at the technical, precision and reliability levels, and also in terms of available services. In this context, the European Union demonstrated willingness to end the dependence on GPS and develop its own system - Galileo.

The present research work arises from the desire to fill a lack in the specialized bibliography concerning a detailed comparison between the current American GPS system and the first system with only civilian motivation, developed by the European Union, Galileo. This will be done by taking into account not only the systems' physical structure and technical performance, but also by analyzing how they are affected by relativistic effects.

Initially a brief characterization of GNSS will be made, with focus on GPS and Galileo. Then, both systems will be characterized in detail in terms of their segments, (Space, Control, and User), available services and signal.

To have an effective usefulness, the current GNSS require time corrections, since synchrony between clocks at different locations is affected by relativistic effects. With this in mind, it will be presented an introduction to the concepts of Einstein's theory of relativity relevant to the corrections to be made, both in the GPS system as the Galileo system. It will be shown that if such corrections were not taken into account we would, taking the example GPS, an accumulation of errors in the order of 12km/day. Finally some high-light will be presented concerning the project for the future of GNSS, still under development.

II. GNSS System

GNSS is a system used to determine the position of an object. These systems are formed by a constellation of satellites with global coverage, which sends signals to a receiver located on the surface, or near, the Earth, allowing it to calculate its location (longitude, latitude and height).

To determine its position the receiver needs to receive a signal from four satellites, in order to determine three spatial coordinates and another relating to time. The calculation method used in this system is called *trilateration (*see figure 1*)*, because this process is used to measure the distance between the receiver and the different satellites.

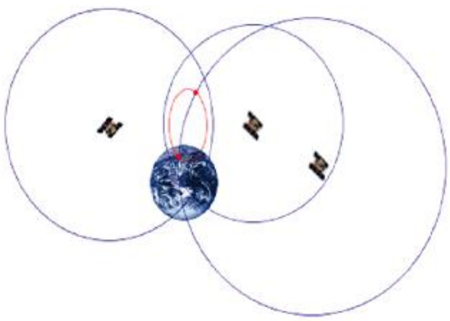

Figure 1 – Trilateration

To determine the distance from a receiver to a satellite requires measuring the time that a signal – with known velocity - takes to reach the receiver, which is done using the well known equation

$$d = c \times t \quad (1)$$

The velocity c is the speed of light, constant and known. The time t corresponds to the time between "departure" and "arrival" of the signal to the receiver. The satellite sends a signal with a message containing its position and time at which the signal was sent. Thus, the receiver, which has its clock synchronized with the satellite clock, will be able to calculate its distance to the satellite.

These systems are used in various applications, including navigation, location, mapping, emergency and aviation.

The U.S.A. and Russia governments developed two systems during the 60/70 decades, the GPS and GLONASS, respectively. However, the systems have different developments. The GPS has become the most used worldwide GNSS, while Glonass had some problems that led Russia to implement a plan to restructure its system during the early XXI century. Under development are the European navigation system Galileo, the Chinese system, BeiDou, the Japanese QZSS, and the IRNSS a system built by India.

III. Comparison between the systems GPS and Galileo

Being the GPS system, currently, the most used in the world for satellite navigation, and being Galileo presented as the future of these systems, it is considered of great importance to perform a better and deeper characterization of these two systems. That is the goal of this work.

A. GPS

GPS is a system characterized by acting on two fronts, providing services to military and civil users. These services are grouped in two formats, known as SPS (Standard Positioning Service) and PPS (Precise Positioning Service). The SPS is set for the civil community, while the PSP is posted only to authorized users of the military and U.S. government agencies, with an accuracy level higher than the SPS.

The GPS system can be divided into three segments:

- The space segment, consisting of satellites that transmit signals used in GPS positioning;
- The control segment, which is responsible for maintaining the system;
- The user segment, which includes all applications and types of receivers.

Spatial segment

- 24 satellites;
- 6 orbital planes, with an inclination of 55º with respect to the equator;
- Sidereal period of 11h 58min;
- Orbital altitude 20.184 km;
- Global coverage.

Currently, the GPS constellation consists of 30 operational satellites, 11 of the class II, 12 class IIR and 7 class IIR-M. (Chidester, 2010)

It is expected to structure another class, called Block III - New Generation Satellites, with the aim of providing sub-meter precision, for more accurate time and increased capability to cross inter-satellite data. (Kaplan and Hegarty, 2006)

Control Segment

The control segment is responsible for detecting and maintaining the satellites in space. It monitors the status of the satellite, holds the configuration of its orbit, and analyzes the signal integrity. It also updates the satellite clock corrections and ephemerides, as well as numerous other parameters essential to determining the position of the user.

The control segment is the OCS (Operational Control System),which consists of a main station, a worldwide network of monitoring and ground control stations. (Sá, 2004)

User segment

The user segment comprises the user equipment (receiver), which processes the signals transmitted from satellites in order to determine its position. This segment is divided in two parts- the civil and military service.

GPS receivers collect the data sent by satellite, and transform them into coordinates, distance, time, displacement or velocity using real time or post processing.

Characterization of the GPS signal

The GPS constellation satellites transmit signals on two L band frequencies, denoted by L1 and L2, which are obtained from the fundamental frequency (f_o=10.23 MHz) multiplied by 154 and 120 to generate the carriers. Therefore the frequencies (L) are:

$$L1 = 10.23\, MHZ \times 154 = 1575.42\, MHz$$

$$L2 = 10.23\, MHZ \times 120 = 1227.60\, MHz$$

With the modernization of GPS, arise three new signals, L2C, L5 and M-code (Kaplan and Hegarty, 2006)

The L2C civil signal, which is an improved version of the L1 C / A that, extends to the civil user the possibility of correcting ionospheric errors.

The M-code, used to update the military code, exclusively for military use in L1 and L2 bands. This code will bring more security, robustness, and reliability to the system.

Finally, we have the L5 signal, also a civil signal that operates at a frequency band L, 1176, 45 MHz (115 f_o), specifically for security applications of human life (*safety-of-life*).

Differential GPS– DGPS

With the need to improve the quality and accuracy of GPS new techniques came up for calculating and reducing errors in determining the position of an object. In this context, it was implemented the DGPS (Differential Global Positioning System).

This method is based on sending two measures to the receiver (Correia, 2003). The first measure is directly received from the satellite. The second measure is sent by a ground station, close to the receiver. Because the ground station and the receiver are geographically close, both measures will be affected by the same error. The ground station processes the signal and, knowing its own 'real' position, makes the correction of the position sent by satellite. Subsequently, the ground station sends the correction to the receiver, which differentially proceeds to correct the information previously received.

With this method it is possible to achieve very high levels of accuracy, depending on the distance between the receiver and the ground station.

B. GALILEO

Recognizing the strategic importance of the applications of GNSS in the early 90's, the European Commission and ESA (European Space Agency) initiated the development of the first generation of a global positioning system, GNSS-1, also known as EGNOS (European Geostationary Navigation Overlay Service).

Despite the immediate benefits, with clear improvements in the integrity and accuracy of the signal, the GNSS-1 does not offer a level of control over the GNSS. Given its dependence on GPS and GLONASS, it cannot offer guarantees about the availability and performance of the signals. In this context, the European agencies are developing the next generation of navigation satellite system (GNSS-2) – named GALILEO - a constellation of satellites with global coverage.

The combined use of Galileo, EGNOS and GPS / GLONASS will increase overall performance, robustness and security inherent to the services performed from GNSS. (Kaplan and Hegarty, 2006)

Services

The GALILEO program is the first system targeted only for civilian use. Thus, its main focus is on user needs and civil global market. (European Commission, 2002)

Open Service (OS) - This service is designed for the common user. Its accuracy is equivalent to the DGPS system, but without resource to an infrastructure on the ground. This service is free and will be available to any user who has a receiver.

The range of broadcast signals available for this service are the bands E5a+E5b (1164 – 1215 MHz) and L1 (1559 – 1592MHz).

Safety of Life (SoL) – In critical services like as marine, aviation and trains, it is necessary to ensure a high performance and safety service to the users. The SoL service is being planned to satisfy those needs. The signs held by this service are the bands E5a + E5b (1164 – 1215 MHz) and L1 (1559 – 1592MHz).

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Commercial Service (CS) - The service will allow the development of professional applications, with high-performance navigation and value-added data. The signals used are the same as in the OS, with the addition of two more encrypted signals (covering the code and data) in the band E6 (1260 – 1300 MHz).

Public Regulated Service (PRS) – The PRS is presented as a robust service (it displays a level of protection better than the previous services) and access control for governmental applications only. The service will offer continuous operation and operate under all circumstances. The frequencies to be used are the E6 (1260 – 1300 MHz) and L1 (1559 – 1592MHz) bands.

Search and Rescue Service (SAR) - The SAR represents the contribution of the Galileo program to search and rescue activities.

Similarly to the GPS, GALILEO offers a vast infrastructure that can be grouped into three segments - Space, Control and User.

Spatial segment

- 30 satellites in MEO orbit (23 222 km altitude);
- Orbital plane inclination of 56º;
- 3 equally spaced orbital planes;
- 9 operational satellites in each plane;
- 1 reserve satellite, ready for operating in each plane.

Control segment

This segment will be responsible for monitoring, reporting and processing the information transmitted by the satellites. The Control and Space segments of GALILEO are connected, through the S band (2483 – 2500 MHz), for telemetry data transmission and remote controls.

User segment

The receiving terminal will allow the user to directly receive the signals in Galileo space (Galileo receiver), to have access to services provided by local and regional facilities, and to benefit from interoperability with other systems. To take full advantage of all available services (global, local and combined), the user needs to be equipped with a multifunction terminal. (European Commission, 2002)

EGNOS

EGNOS is operational since 1 October 2009.This program provides a service to a broad class of users, including the general public, experts and critical security. EGNOS is presented as a tool for future applications of Galileo.

Currently the system offers a complement to GPS systems, focusing on the European area (see Figure 8), and providing higher levels of precision and signal integrity. This service is provided openly, but its use depends on the availability of GPS.

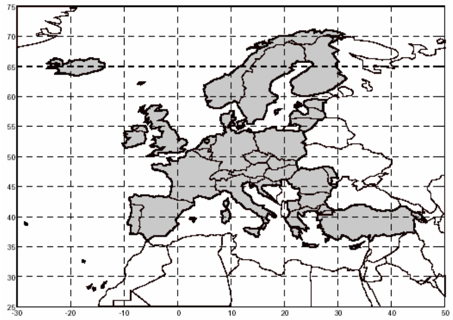

Figure 2 –Covered area by EGNOS
Source: (European Commission, 2002)

Characterization of the GALILEO signal

GALILEO will provide six navigation signals in the frequency bands 1164 - 1215 MHz (E5band), 1260 - 1300 MHz (E6 band), and 1559 - 1592 MHz (E2-L1-E1 - or simply L1band).

Interoperability

Interoperability can be defined as the combination of information (e.g. navigation data) from two navigation systems (e.g., GPS and GALILEO), on the user receiver, with the purpose of achieving a better performance than by employing any of the systems individually. (Kaplan and Hegarty, 2006)

Signal in space - In order to minimize complexity and cost of the receiver, GALILEO signals - E5a and E2-L1-E1 will be transmitted using frequencies L5 and L1 identical to GPS signals, respectively.

Geodesic reference system - The reference system for space coordinates and time of the program will be based on different stations and clocks from those that are used by GPS. GALILEO program will adopt the GTRF (Galileo Terrestrial Reference Frame) which is an independent adaptation of the ITRS (International Terrestrial Reference System). The GPS system uses the reference system WGS-84 (World Geodetic System - 1984) which is also an adaptation of the ITRS. The differences between WGS-84 and GTRF won't be greater than 2 cm, which does not affect most of the users (Miller, 2004). This implies that the WGS-84 and GTRF will be practically identical (the reference coordinates are compatible).

Time reference system –Like the GPS Timing System, which coordinates its time through the UTC (Coordinated Universal Time), Galileo will have its own time scale, the GST (Galileo System Time). The GST will be coordinated by IAT (International Atomic Time). There is a difference between these two time scales, known as GGTO (GPS - Galileo Time Offset), that has to be taken into account when matching data from the two systems. This offset will be calculated and sent to users in real time, on the Galileo navigation message. (Forrest, 2004)

IV. Relativity in GNSS

In order to fulfill their function effectively GNSS systems must take into account relativistic effects. The satellites are affected by relativity in three different ways, namely gravitational shift of the frequency of clocks on the satellites, since the rhythm of a clock increases with its distance from a center of gravitational attraction; Time dilation that generates a delay of a satellite clock compared to a clock on Earth, due to the relative motion between them; Sagnac effect which arises from rotation of the Earth during the signal propagation.
The analysis of these effects are based on the Theory of Relativity conceived by Albert Einstein in the twentieth century - Special Relativity in 1905 and General Relativity (gravity) in 1915.

The postulates of this theory can be defined as:

1. The laws of physics are the same in all inertial frames;

2. Light propagates in vacuum at a constant velocity, c, independent of the state of motion of the source;

3. In a small region of space and time, it is impossible to distinguish between the gravitational field due to mass and the gravitational field due to acceleration.

The Theory of Relativity is based on two theories, Special Relativity expressed in the first two postulates and General Relativity in the third postulate.

A. Time dilation

An observer at rest in the ECI will see the satellite clock tick at a lower rate by the factor

$$1-\frac{1}{\gamma'}=1-\sqrt{1-\frac{v_S^2}{c^2}} \quad (2)$$

$$\approx -\frac{1}{2}.\frac{v_S^2}{c^2}$$

The value of v_s (satellite velocity) is constant and can be obtained from the following equation

$$v_s=\sqrt{\frac{GM}{r_s}} \quad (3)$$

where r_s is the orbital radius of the satellite. Since the equatorial radius of the Earth is $r_e = 6\ 378\ km$ and the orbital altitude of the GPS satellites, is 20 184 km. we obtain $r_s = 26\ 562\ km$.

If we refer to the GALILEO constellation $r_s = 29\ 600\ km$, since its orbital plane is higher (23 222 km).

The Earth's gravitational parameter is defined as (European Union, 2010) (GPSWing, 2010)

$$GM=\mu=3.986005\times 10^{14}\ m^3 s^{-2},$$

where G is the universal gravitational constant and M the mass of the Earth. There results, $v_s = 3\ 874\ m\ s^{-1}$ for GPS and $v_s = 3\ 670\ m\ s^{-1}$ for the Galileo system.

Consequently, taking into account equation (3) we get an approximate value for time dilation

$$\approx -\frac{1}{2}.\frac{v_S^2}{c^2} \approx -8.349\times 10^{-11}$$

A reference clock that is fixed on the earth geoid is also moving on the ECI, due to the Earth's rotation (Ashby, 2006). However, its velocity is lower than the satellites' velocity. At the Equator the Earth rotates at $w.r_e \approx 465\ m\ s^{-1}$, where $w = 7.292115\times 10^{-5}\ rad.s^{-1}$ is the angular velocity

The difference in time between a clock at rest in the ECEF frame and the clock at rest in the ECI frame is obtained from the equation

$$1-\frac{1}{\gamma''}=1-\sqrt{1-\frac{(w.r_e)^2}{c^2}} \quad (4)$$

$$\approx -\frac{1}{2}.\frac{(w.r_e)^2}{c^2} \approx -1.203\times 10^{-12}$$

Therefore, the time dilation between the clock in orbit and a clock on the earth surface is given by

$$1-\frac{1}{\gamma}=\frac{1}{\gamma'}-\frac{1}{\gamma''} \quad (5)$$

$$\approx -8.229\times 10^{-11} \approx -7109\ ns.d^{-1}$$

A similar analysis can be performed for the Galileo system. Only the factor $\frac{1}{\gamma'}$ will suffer changes, because the variables on which the factor $\frac{1}{\gamma''}$ depends are the same, for both systems. Considering that, in this case, the velocity of the satellite will be$v_s = 3\ 670\ m\ s^{-1}$, the predicted time dilation is

$$\approx -7.613\times 10^{-11} \approx -6578\ ns.d^{-1}$$

B. Gravitational effect

The influence of the gravitational field in the beat clock is another relativistic effect to consider.

The gravitational potential in a specific point in the Earth's surface is given by

$$\Phi(r)=-\frac{GM}{r}\left(1-J_2\frac{{a_1}^2}{c^2}\frac{(3z^2-r^2)}{2r^2}\right) \quad (6)$$

where a_1 corresponds to the radius of a clock that is at rest (equator), r to the orbital radius of the satellite and J_2 to the earth's quadrupole moment coefficient that is equal to

$$J_2=1.08263\times 10^{-3}$$

The gravitational potential measured at the equator, i.e. for z = 0, is obtained from the following equation

$$\Phi_0=-\frac{GM}{a_1}\left(1+\frac{J_2}{2}\right) \quad (7)$$

To calculate the gravitational potential of a clock in orbit it is possible to use equation

$$\Phi_S = -\frac{GM}{r_S} \tag{8}$$

where r_S is the orbital radius of the satellite.
Using equations (8) and (9) we found the temporal error caused by the gravitational field

$$\frac{\Delta t}{t} = \frac{\Phi_S - \Phi_0}{c^2} \tag{9}$$

$$\approx 5.288 \times 10^{-10} \approx 45685\, ns.d^{-1}$$

A similar analysis for the Galileo system yields

$$\approx 5.471 \times 10^{-10} \approx 47270\, ns.d^{-1}$$

C. *Sagnac Effect*

A receiver at rest on the Earth's surface will experience a shift in its position during the period in which the signal, coming from the satellite, propagates. This phenomenon arises from the rotation of the Earth, and is known as Sagnac effect.
The correction for this error is given by

$$\Delta t_{Sagnac} = \frac{R.v}{c^2} = \frac{2w.A}{c^2} \tag{10}$$

with $v = w \times r(t)$

$A = \frac{1}{2} r(t) \times R$

where $r(t)$ represents the position of the receiver at time t, w the average angular velocity of the Earth, R the distance between the transmitter and receiver at the time of transmission, and A the area swept by a vector from the axis of rotation to where the signal is received.
To determine the maximum error committed to a receiver at rest on the geoid surface, it can be assumed that $r(t) = 6\,378\ km$, $R = 26\,562\ km$, $c = 299\,792\,458\ m\ s^{-1}$, and $w = 7.292115 \times 10^{-5}\ rad.s^{-1}$
Thus we have

$$\Delta t_{Sagnac} = \frac{2w.A}{c^2} \approx 133\ ns \quad para\ o\ GPS$$

For Galileo is necessary to reformulate the value of variable R, which becomes $R = 29\,600\ km$
Then

$$\Delta t_{Sagnac} \approx 153\ ns \quad \text{para o Galileo}$$

After consideration held on key relativistic errors that affect GNSS we can still add a last error caused by the imperfection of the circular orbits. Although this effect causes an error lower than the others, it remains significant, with a value of the order of magnitude of nanoseconds. (Ashby, 2003)

D. *Eccentricity correction*

The orbits of the satellites, so far considered as perfectly circular (e = 0), suffer from disorders that cause an orbital eccentricity. This means that the satellite reaches different heights and speeds along its orbit, which, as we saw in the previous sections, causes changes in the beat of atomic clocks.
The speed v_S and gravitational potential Φ_S will suffer periodic changes due to changes in the orbital radius of satellites, r_S.
The correction for the error due to orbital eccentricity can be expressed by the equation

$$\Delta t_r = +\frac{2.r.v}{c^2} \tag{11}$$

where $\mathbf{r}$ and $\mathbf{v}$ represent the position and velocity, respectively, at the time of transmission. (Ashby, 2003)
This equation can be approximated by

$$\Delta t_r \approx +\frac{2\sqrt{GM.a}}{c^2} e \sin E \tag{12}$$

$$= 4.4428 \times 10^{-10} e \sqrt{a} \sin E \qquad s.m^{-\frac{1}{2}}$$

($e, \sqrt{a}, \sin E$) correspond to the orbital eccentricity of the orbit of the satellite, the semi-major axis and eccentric anomaly of the satellite orbit, respectively.
The orbit of a satellite has an eccentricity < 0.02 (Haustein, 2009). Considering the maximum value of eccentricity (e = 0.02) the maximum error caused by eccentricity is 46 ns.

This correction is performed by the user segment of the navigation system. However, its introduction in the signal transmitted by the satellites would make more sense, since they are closer to the time of the coordinated system itself (e.g. GPS system time). (Ashby, 2003)

E. Corrections to be made

The clocks on the satellites suffer from two distinct effects, one that causes a delay in their rate of vibration (time dilation), and a second one that produces an opposite effect (gravitational effect).

Adding the two errors we can see that a clock embedded in a satellite, for example in GPS, tick about 39 μs / day, faster than a clock in the geoid. This is equivalent to an accumulated error in the order of 12 km/day, which would be inconceivable for a positioning system.

Interestingly, the two errors mentioned, when analyzed for the orbital radius of 9 550 km, or 3000 km above the geoid, these two effects cancel each other. Above this radius the gravitational effect is shown with more emphasis on the error obtained, as demonstrated by results obtained. Below this limit there is a greater contribution of the Doppler effect. (Ashby, 2002)

In table 4 we can see the errors to correct the GPS and Galileo

Error	**GNSS System**	
	GPS	**GALILEO**
Time dilation (µs/day)	-7.1	-6.6
Gravitacional effect (µs/day)	45.7	47.3
Sagnac effect (µs/day)	0,133	0,153

Table 4 – Errors caused by relativistic effects

GPS clocks are set to oscillate at a frequency of 10.23 MHz. However, is essential to include in this frequency the necessary relativistic corrections.

As mentioned previously the clocks are ahead at about $4.465 \times 10^{-10} \approx 39\,\mu s/dia$, so we should apply the following correction

$$10.23 \times 10^{6} - (1 - 4.465 \times 10^{-10}) \qquad (13)$$

$$= 10.22999999543\ MHZ$$

The oscillator must be set to a frequency $10.22999999543\ MHZ$, so that an observer on the Earth's surface, 'sees' the clock at nominal frequency of 10.23 MHZ.

For the Galileo system, we should introduce an offset to the oscillator clock of $4.71 \times 10^{-10} \approx 41\,\mu s/dia$

F. Future

Up to the present day, GNSS systems are based on a Newtonian model that requires relativistic corrections (essential!) to maintain its effectiveness and accuracy as a positioning system. This model uses two reference systems, ECI and ECEF for time and position, respectively.

However, a system based on a model that requires corrections will not be the ideal formula. In this sense Bartolomé Coll during the first decade of this century, has been studying a fully relativistic system, that is, a system that needs no corrections. This is the basis of the concept SYPOR (Système de Positionnement Relatives). This program was thought, possibly, to incorporate the new European system - Galileo. The SYPOR is a project that is still within a framework of theoretical construction. (Pascual-Sanchez, 2007)

The SYPOR plans to separate the GNSS in two hierarchical systems, namely (Coll, 2006):

1. A primary system, independent of the Earth's surface, which includes the satellite constellation - the primary system for positioning with four dimensions;
2. A secondary system, dependent on the Earth's surface, linking the terrestrial reference system (WGS 84 or ITRF) to the primary system

This application will allow for a GNSS system fully autonomous and relativistic, without the need to correct errors that currently occur due to relativistic effects, increasing in this way the effectiveness and accuracy of the positioning system.

V. Conclusion

The increased use of GNSS in the world, and the wide range of services in various areas makes the constant improvement in terms of effectiveness and reliability of these systems a very important issue.

Throughout this work we can see the differences between GPS and Galileo from each system basic idea and motivation, to the model construction of its segments. Unlike GPS, Galileo emerges as a fully public system designed to give the European Union a positioning system independent of the American system. However these two systems will not be completely independent, since they are also being implemented in the interests of interoperability, thus allowing a receiver to receive signals coming from the two systems.

Both GPS and Galileo have their space segment in MEO orbit and the speed of its satellites is in the order of km/s, which implies the appearance of errors due to relativistic effects. The errors in both systems are similar as well as how to correct them. The errors arise primarily from the fact that the satellites are in a weaker gravitational field, which implies an advance of the clock on the satellite, compared to a clock on the geoid. Also critical is the satellites motion, which causes a delay in the satellite clock relative to another clock on the Earth.

The correction to be made on the clocks due to relativistic effects is $39\mu s/day$, in the case of GPS and $41\mu s/day$ for Galileo. This discrepancy is explained by the difference between the orbital radius of the constellation of each of these two systems - for GPS $r = 20\,184\,km$ and for Galileo $r = 23\,222\,km$. The dissimilarity observed in the orbital radius implies a lower velocity of satellites for Galileo,$v_s = 3\,670\,m\,s^{-1}$ and $v_s = 3\,874\,m\,s^{-1}$ for GPS.

Adding these two factors we observe a time dilation superior to GPS, because of the higher speed of its constellation, and in opposition a greater gravitational effect on Galileo derived from its larger orbital radius. If these effects were not corrected the positioning service would accumulate an inaccuracy in the order of 12 km/day, for both systems, more precisely, 11.69 km/day for GPS and 12.29 km/day for Galileo.

The future of GNSS systems passes through the change of the actual Newtonian model to a fully relativistic model, enabling a continuous improvement in the accuracy, reliability and integrity of the system, without making corrections necessary in present systems. This system is being studied and developed by the project SYPOR since the beginning of the XXI century.

VI. Bibliography

- Ashby, N., 2002, “Relativity and the Global Positioning System”, Physics Today;
- ______, 2003, “Relativity in the Global Positioning System”, Living Reviews Relativity, 6;
- ______, 2006, “Relativistic effects in the Global Positioning System”, Department of Physics, University of Colorado;
- Chidester, Maj Wesley, 2010, “GPS status and modernization”, GEOSpatial Information Systems for Transportation Symposium, Charleston, WV, 12-14 April;
- Coll, Bartolomé, 2006, “Relativistic Positioning Systems”, Systèmes de reference relativists, SYRTE-CNRS, Observatoire de Paris, France;
- Correia, Carlos, 2003, Sistema GPS – Introdução, Sistemas de Telecomunicações II, FEUP, Porto;
- Dutt, V.B. et al, 2009, “Investigation of GDOP for Precise user Position Computation with all Satellites in view and Optimum four Satellite Configurations”, J. Ind. Geophysics Union, Vol.13, No.3, pp.139-148;
- ESA, 2008, Lançamento do Satélite Giove – B, Consult. 12 Novembro 2010, disponível em http://www.esa.int/esaCP/SEMIKG2QGFF_Portugal_0.html;
- European Commission, 2002, “Galileo: Mission High Level Definition”;
- European Union, 2010, “European GNSS (Galileo) Open Service”, Signal in Space Interface Control Document;
- Falcone, Marco et al., 2006, “Giove’s Track”, GPS World;
- Forrest, W. M., 2004, ”Interoperability of the GPS and Galileo Timescales for Positioning and Metrology”, IEEE, Thales, UK;
- Global Positioning System Wing, 2010, “Navstar GPS Space Segment/Navigation User Interfaces”, Interface Specification IS-GPS-200 Revision E;
- Haustein, Mario, 2009, “Effects of the Theory of Relativity in the GPS”, Chemnitz University of Technology;
- Horváth, Tamás, 2002, “”Performance Comparison of Wide Area differential GPS Systems”, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada;

- IGS, 2009, "IGS Products", International GNSS Service, 17 de Novembro 2010, disponível em http://igscb.jpl.nasa.gov/components/prods.html;
- JAXA (*Japan Aerospace Exploration Agency*), 2010, "Launch Result of the First Quasi-Zenith Satellite 'Michibiki'", consulta a 5 de Fevereiro de 2011, disponível em http://www.jaxa.jp/press/2010/09/20100911_h2af18_e.html;
- ______, 2010, "Quasi-Zenith Satellite System Navigation Service",Interface Specification for QZSS, ver.1.42;
- Kaplan, Elliot D., Hegarty, Christopher J., 2006, "Understanding GPS: Principles and Applications", Artech House, Boston;
- Kulkarni, Sagar, 2007, "India to develop its own version of GPS", Hyderabad, consulta a 2 de Fevereiro de 2011, disponível em http://www.rediff.com/news/2007/sep/27gps.htm
- Langley, R. B., 1996, "Propagation of the GPS signals", GPS for Geodesy, Springer, Berlin, pp. 103 - 140;
- Majithiya, P., et al.,2011,"Indian Regional Navigation Satellite System", Inside GNSS, January/February;
- Miller, J., 2004, "GPS and GALILEO: Evolution towards GNSS"", Proceedings of ION 2004 National Technical Meeting, 26-28 January, California, pp. 73 – 91;
- Nelson, Robert A., 2003, "Practical Relativistic Timing Effects in GPS and Galileo", CGSIC Timing Subcommittee Meeting;
- Pascual-Sánchez, J. F., 2007, "Introducing relativity in global navigation satellite systems", Annual Physics (Leipzig) 16, No. 4, 258 - 273
- Ray, J. K., (2006), "What receiver technologies exist for mitigating GNSS pseudo-range and carrier phase multipath?", Inside GNSS, pp. 25 – 27;
- Rizos, C., (1999), "Principles and Practice of GPS Surveying", School of Geomatic Engineering, The University of New South Wales, Australia;
- Sá, N. C., 2004, "GPS: Fundamentos e aplicações", IAG/USP, Departamento de Geofísica;
- SEEBER, G.,2003, "Satellite Geodesy: Foundations, methods and applications". Walter de Gruyter, New York;