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Relativistic Corrections in the European GNSS Galileo

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Abstract

Navigation space missions are mainly timing missions. They use extremely accurate atomic clocks embarked on their satellites and as part of their ground infrastructure. Clocks in motion with respect to each other and moving in different gravitational potentials are the perfect mix to experiment relativistic effects. Despite the appearances, these effects are not negligible. This paper describes how these effects are being tackled in the European GNSS Galileo.

1. Introduction

This paper provides an overview of the relativistic effects in the satellite navigation systems and provides details on their treatment in the European satellite navigation system Galileo.

2. Galileo, the European Global Navigation Satellite System

The Galileo global navigation satellite system, joint initiative by the European Union and the European Space Agency, is one of the most ambitious and technologically advanced service-oriented systems being developed in Europe. Galileo is a navigation satellite program under civilian control, in comparison with other Global Navigation Satellite Systems (GNSS) which have been designed in the late sixties for military applications. It will provide positioning, navigation and timing signals on a global scale.

The Galileo system is based on a constellation of 30 satellites and on a number of Control Centers, implemented on European ground, to provide for the control of the constellation, to perform the navigation mission management and to monitor the system performance.

The Galileo system can be decomposed, at the first level, into the following Segments:

- the Space Segment, consisting of 24 satellites of the Galileo reference constellation plus 6 in orbit spares . Each Galileo satellite carries on board two passive Hydrogen masers and two Rubidium atomic clocks. The satellites are evenly distributed over three orbital planes with the nominal average semi-major axis of 29601.297 Km and the inclination of 56 degrees [3];
- the Ground Segment (composed of the Control Segment and of the Mission Segment),
- and a User Segment.

The Ground Segment takes care of two main tasks: to control the satellite constellation and to provide the navigation message. The Ground Segment will include two Galileo Control Centers, one in Fucino (central Italy) and the second close to Munich (Germany). They are connected to a worldwide network of Galileo sensor stations to monitor the Galileo signals. Satellite orbits and clock parameters are computed relying on this sensors network and then disseminated to users via the navigation message broadcasted by the satellites.

The foundation of Galileo are the high precision clocks:

- on board of the satellites (including the passive Hydrogen maser, the most stable clock ever flown in a navigation missions [5]),
- and in the Precise Timing Facility (PTF) in the Galileo Ground Control Center. The two redundant PTFs produce the physical representation of the Galileo System Time (GST). Each of them is equipped with 2 active Hydrogen masers and 4 Cesium clocks [6].

3. Relativity in the Satellite Navigation Systems

In terms of the Relativity Theory, a satellite is a collection of time and coordinates events in space and at each event the satellites broadcast the navigation message that contains almanac, ephemeris and other data [3].

The relativistic effects affecting the performance of any Global Navigation Satellite System, such as

Galileo, are many and contributing with different magnitudes to the overall error on accuracy.

Hereafter, only the four main effects are considered. They are, in order of importance, the gravitational "blue shift" effect, the time dilation "red shift" effect (special relativity Doppler effect of second order), the Sagnac effect and the Shapiro effect.

As shown in [1], [2] and other sources, the impact of the higher order effects at the navigation users can be neglected.

3.1. Gravitational Frequency Shift

As shown in [2], the relative frequency shift between a clock experiencing the gravitational potential $\Phi+\Delta\Phi$ and the one at the gravitational potential Φ is:

$$\frac{\Delta f}{f} = \frac{\Delta\Phi}{c^2} \tag{1}$$

For an unperturbed circular Keplerian orbit, the gravitational potential omitting the higher-order harmonics in line with the approach taken in [2] and [12] is given by

$$\Phi_{sat} = -\frac{GM_E}{r} \tag{2}$$

where r is the radius of the satellite orbit.

In turn, for the reference clock, being at rest at the geoid surface at the equator, the gravitational potential is

$$\Phi_{\oplus} = -\frac{GM_E}{a}\Big(1+\frac{J_2}{2}\Big) \tag{3}$$

where a is the semi-major axis of the ellipsoid and J_2 is the Earth's quadrupole moment coefficient. Higher moments are not considered in line with the ITU recommendation [12].

Thus, the gravitational frequency shift at the nominal Galileo orbit is:

$$\begin{gathered}\frac{\Delta f}{f} = -\frac{\Phi_{sat}-\Phi_{\oplus}}{c^2} = \\ -\frac{GM_E}{c^2 r} - \Big(-\frac{GM_E}{c^2 a}\Big(1+\frac{J_2}{2}\Big)\Big)\end{gathered} \tag{4}$$

With $r = 29601297\ m$, $c = 299792458\ m/s$, $a = 6378136.55\ m$, $GM_E = 3.986004418\times10^{14}\ m^3/s^2$ and $J_2 = 0.0010826267$ (see [3]), Eq. 4 gives the frequency shift of $+5.4590\times10^{-10}$. The orbiting clock will appear, when observed from the Earth, as running faster because of this gravitational blue-shift. Over one day period the clock in orbit accumulates the offset of 47.17 microseconds with respect to the reference clock on ground. This corresponds to a ranging error of about 14 kilometers.

There is also a periodic relativistic frequency shift due to the orbit eccentricity, the corresponding time correction is given by the following equation (as expressed both in [2] and [12]):

$$\Delta t_r = \frac{2\sqrt{GM_E}}{c^2} e\sqrt{A}\sin E \tag{5}$$

where

- e is the eccentricity of the satellite orbit,
- A is the semi-major axis of the satellite orbit, and
- E is the eccentric anomaly of the satellite orbit.

3.2. Time Dilation

Another important relativistic effect in Galileo is that related to the relative motion of the clocks (onboard the satellites and on the ground). Clocks in motion with velocity v tick slower when viewed from an observer in an inertial frame at rest. This relation is well known and was formalized by the Dutch physicist Hendrik Lorentz. Lorentz defined these transformations before the publication of the Einstein's seminal paper of 1905 moving from a different approach shared with FitzGerald: the Lorentz-FitzGerald contraction hypothesis. Later Einstein interpreted and explained the contraction hypothesis in the light of the principle of the constant speed of light in any inertial frame of reference and the principle of relativity.

The Lorentz transformation can be written as:

$$t' = \sqrt{1-\beta^2}\,t \tag{6}$$

where $\beta = v/c$.

So a clock moving with speed v with respect to a clock resting in an inertial frame of reference will beat slower. Introducing the binomial expansion formula $(1+x)^n = 1+nx+n(n-1)/2!+...$ and truncating at the second order, we have:

$$\sqrt{1-\beta^2} \approx 1-\frac{1}{2}\beta^2 \tag{7}$$

As shown in [2], the relative frequency red-shift due to the relative motion of the satellite with respect to the reference clock at rest at the geoid at the equator is:

$$\frac{\Delta f}{f} = -\frac{v_{sat}^2}{2c^2} + \frac{(a\Omega_E)^2}{2c^2} \tag{8}$$

where Ω_E is the mean angular rotation rate of the Earth and v_{sat} is the orbital speed of the Galileo satellite.

With $\Omega_E = 7.2921151467\ rad/s$ and $v_{sat} = 3669.6\ m/s$ assuming a circular orbit at the Galileo altitude, the relative frequency red-shift for the Galileo satellite clock is -7.3709×10^{-11}. This is accumulates to the clock offset of about -6.37 microseconds per day.

3.3. The Sagnac Effect

The classical Sagnac effect concerns the propagation of electromagnetic signals in rotating reference frames. An interpretation for the Sagnac effect for GNSS can be found in [2]. It occurs due to the receiver motion with respect to the satellite position at the time of signal emission: the receiver is still moving (e.g. due to the Earth rotation) over the time interval between signal emission and the signal reception. In more details, for a signal which is transmitted by the satellite at the position $\vec{R}_{sat}$ at the time t_{sat} and received by the receiver on ground at the position $\vec{R}_{user}$ at the time $tuser$ while the receiver is moving with the speed $\vec{v}_{user}$ with respect to the satellite:

$$c^2(\Delta t)^2 = |\vec{R}_{user} + \vec{v}_{user}\Delta t - \vec{R}_{sat}|^2 \tag{9}$$

where $\Delta t = t_{user} - t_{sat}$.

As also demonstrated in [2] this can be solved as

$$\Delta t_{Sagnac} = \frac{\vec{v}_{user} \cdot (\vec{R}_{user} - \vec{R}_{sat})}{c^2} \tag{10}$$

[13] gives a convenient form to compute the Sagnac correction for a user receiver at a fixed location (i.e. moving only due to the Earth rotation):

$$\Delta t_{Sagnac} = \frac{\omega_E}{c^2}(x_U \cdot y_s - x_s \cdot y_U) \tag{11}$$

where

- ω_E is the Earth's angular rotation velocity
- x_{user}, y_{user} are the x- and y-component of the user position vector in the chosen terrestrial reference frame (Galileo Terrestrial Reference Frame (GTRF) for Galileo), at the time of signal transmission,
- x_{sat}, y_{sat} are the x- and y-component of the satellite position vector in the same reference frame as chosen for the user position (GTRF for Galileo), at the time of signal transmission at satellite.

For the specific geometry of the Galileo constellation, the maximum Sagnac effect is about 153 ns for a user receiver stationary on the ground.

It is worth noting that the gravitational effect is by far the largest of all relativistic effects: more than six times larger than the speed effect and two orders of magnitude larger than the Sagnac effect. General relativity, in other words, dominates over special relativity, as far as GNSS relativistic effects are concerned.

3.4. The Shapiro Correction

Einstein suggested three tests to verify his general theory:

- The gravitational red shift of spectral lines;
- The deflection of light by the Sun;
- The precession of the perihelia of the orbits of the inner planets.

A fourth test was added later:

- The time delay of radar echoes passing the Sun.

In recent years the development of high-speed electronics and high-power radar has offered the possibility of measuring motion as a function of time with the accuracy needed to verify the Einstein's laws. I. I. Shapiro [14] designed an experiment, that was run at the Lincoln Laboratory, aimed to carry out measurements of the time required for a radar signal to go from one point ($r = r_1$, $\theta = \pi/2$, $\phi = \phi_1$) to a second point ($r = r_2$, $\theta = \pi/2$, $\phi = \phi_2$).

In navigation this effect is classified as minor even if it is a direct proof of the general theory. Its correction amount to centimetres and Galileo takes it into account. Shapiro carried out measurements of the time required for radar signals to travel to the inner planets and be reflected back to earth. From the historical point of view is worth mentioning the severe difficulties Shapiro met while performing the experiment using a 7840MHz Haystack radar at the Lincoln laboratory; Shapiro needed to know the location of the centres of the Earth and of Mercury at a precision level that was unprecedented.

This effect is described as due to the deflection a photon perceive when passing by a mass. In the detail the effect is due to the effective time metric obeying the Schwarzschild definition. A very detailed and amazing description of the Schwarzschild solution and the Shapiro delay can be found in the S. Weinberg's book "Gravitation and Cosmology" [4]

In [1], the Shapiro delay is given by the following formula:

$$\Delta t_s = \frac{2GM_E}{c^3} \ln\left(\frac{r_{sat} + r_{user} + d}{r_{sat} + r_{user} - d}\right) \tag{12}$$

where r_{sat}, r_{user} are modules of the satellite position and user position respectively.

4. Relativistic Corrections Implemented in Galileo

The relativistic effects analysed so far would introduce significant errors in the ranging and consequently positioning accuracies of a GNSS system, unless they are carefully taken into account in the system design and user algorithms.

In GPS and GLONASS the systematic relativistic net effect (i.e. the combination of the gravitational frequency shift and the time dilation due to the orbital motion of the satellite) is compensated by adequately offsetting the onboard clocks before launch, while time-varying effects are corrected at user receiver level.

It is anticipated that this is not the approach in the Galileo system. As explained in detail in the following paragraphs, the correction of relativistic errors is performed at user receiver level, on the basis of information broadcasted through the navigation message.

4.1. Satellite clock

The major contributions of the constant relativistic effects to the frequency offset of a user clock on geoid and a satellite clock at the Galileo orbit (assuming a circular orbit and neglecting contribution of J_2 and higher moments of the Earth's gravitational potential) are summarized in Table 1. As pointed in the introduction, the second order effects are not considered here. Shapiro correction is also not considered in Table 1 since it is negligible comparing to the other contributions.

Table 1
Major constant relativistic effects on user and satellite clocks

Effect	User clock at geoid	Galileo SV clock
Earth's mass	$-6.953 \cdot 10^{-10}$	$-1.498 \cdot 10^{-10}$
Quadrupole moment J_2	$-3.764 \cdot 10^{-13}$	neglected
Earth spin / SV motion	$-1.203 \cdot 10^{-12}$	$-7.491 \cdot 10^{-11}$
Total SV frequency offset		$+4.7219 \cdot 10^{-10}$

Relativistic effects on Galileo clocks have been successfully validated already during the GIOVE mission with the accuracy of 10^{-12} (see e.g. [11]).

At the time of writing, the frequency of the Galileo satellite clocks is not corrected to compensate the relativistic shift, unlike GPS. Nevertheless, the capability to adjust the satellite clock frequency, e.g. in order to align it to GST, is available. Galileo onboard clocks will be periodically aligned to GST both and phase and frequency to maintain these parameters within the limits acceptable from the system operations point of view. Furthermore, as an experiment, the relativistic frequency shift of GSAT0102 (PRN E12) was corrected in orbit, after launch.

The frequency of the Galileo satellite clock deviates from the nominal due to the frequency initialization uncertainty, the integrated effect of the frequency instability and the systematic relativistic frequency shift previously addressed. The Galileo Orbitography and Synchronization Processing Facility (OSPF) estimates the total satellite clock offset versus the Galileo System Time (GST; it is the internal time reference utilized across all the Galileo system) and models it with a second order polynomial. The polynomial coefficients are broadcasted to users in the Galileo navigation message. The OSPF pre-processing (see the sub-section below) compensates the relativistic frequency shift due to the orbit eccentricity (see Eq. (5)). Therefore, this broadcasted clock model absorbs also the systematic relativistic frequency shift of the satellite clocks for a circular orbit. The validity of this approach is verified by the Galileo test results indicating excellent positioning and timing performance (see e.g. [10]).

Table 2 summarizes the systematic relativistic frequency shift on the satellite clocks for Galileo, GLONASS and GPS for both the theoretical values and the ones specified in the corresponding Signal In Space Interface Control Documents (ICDs). Note the inverse sign of the correction with respect to the estimated relativistic frequency shift.

Table 2
Frequency shift of the satellite clocks in GPS, GLONASS and Galileo

GNSS	Theory	Systematic correction as per the system ICD
GPS	$-4.4647 \cdot 10^{-10}$	$-4.4647 \cdot 10^{-10}$ [8]
GLONASS	$-4.3582 \cdot 10^{-10}$	$-4.36 \cdot 10^{-10}$ [9]
Galileo	$-4.7219 \cdot 10^{-10}$	None

4.2. User Receiver Processing Algorithm

The Test User Receiver (TUR) is a reference user receiver defined and procured by the Galileo project as a tool for system verification. TUR definition includes the reference Galileo user receiver algorithm.

Table 3 summarizes the treatment of the relativistic effects in the reference algorithm.

According to the reference algorithm, the Sagnac correction ΔS shall be computed following Eq. (11).

Note that GTRF is the ECEF realization as adopted by Galileo.

The reference user algorithm applies Sagnac correction to the raw pseudorange measurements.

In line with the Galileo OS SIS ICD [3], the algorithm also applies the relativistic satellite correction due to the satellite orbit eccentricity in the computation of the satellite clock offset vs. GST, Δt_r:

$$\Delta t_r = Fe\sqrt{A}\sin E \tag{13}$$

where:
$F = -2\sqrt{\mu}/c^2 = -4.442807309 \cdot 10^{-10}\ s/m^{1/2}$, and

$\mu = GM_E$ is the Earth gravitational constant.

Note that Eq. (13) is equivalent to Eq. (5).

Table 3
Correction approach for the relativistic effects

Effect	Correction
Systematic frequency shift at the circular orbit	Not corrected on board and absorbed in the broadcast satellite clock model. Compensated in the user algorithm when applying the model.
Frequency shift due to the orbit eccentricity	Corrected in the user algorithm according to the ICD equation.
Higher order relativistic effects	Not corrected since negligible for typical navigation purposes
Sagnac effect	Corrected in the user algorithm

4.3. Ground Segment

Relativistic effects need to be accounted for in the Galileo ground segment processing as well, in particular in the following:

– generation of the aforementioned system reference time, Galileo System Time (GST),

– satellite orbit determination and clock synchronization.

4.3.1. Galileo System Time (GST) generation

The high-level requirement for the Galileo system reference time, GST, is that of being a continuous coordinate time scale in a geocentric reference frame, steered towards the UTC modulo 1 second.

The physical representation of GST, the so-called "GST Master Clock", is generated by two redundant Galileo Precise Time Facilities (PTF) which are located at the Galileo Control Centers in Fucino and Oberpfaffenhofen. GST(MC) is a steered output of an active Hydrogen maser.

GST(MC) is steered to the international reference timescale UTC modulo 1 second, i.e. the steering aims to minimize the fractional GST(MC)-UTC offset, but the UTC leap seconds are not introduced in GST. Therefore, the integer GST(MC)-UTC offset is changing after each leap second.

As of July 2015, GST(MC) is ahead of UTC by 17 seconds. According to its definition, GST(MC) frequency follows that of International Atomic Time (TAI), one of the fundamental timescales maintained by BIPM.

According to the Declaration of the CCDS, BIPM Committee Consultative Definition Seconde (1980), "TAI is a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit."

TAI can be regarded as the time coordinate in the General Relativity Framework. In terms of implementation, the Galileo Time Service Provider (TSP), whose function is currently performed by the Galileo Time Validation Facility (TVF), predicts UTC from the real-time realizations UTC(k) provided by the participating European UTC laboratories.

GST(MC) offset to the UTC(k)'s is measured using Two Way Satellite Time and Frequency Transfer (TWSTFT) (see [15]) and GPS Common View (see [16]) methods.

From these measurements and the PTF internal clock data, TVF computes the offset between the free-running active Hydrogen maser at PTF vs. the UTC prediction. No relativistic corrections are introduced into the measured GST(MC)-UTC(k) offsets nor in the internal PTF clock measurements.

Based on the estimated time offset, TVF daily computes the GST(MC) frequency corrections. This correction compensates the combined effect of the maser instability and its relativistic frequency shift.

According to [7], "the relativistic offset is fully absorbed in the steering of GST to UTC: the scale unit of UTC is adjusted within the uncertainty of the combined ensemble of primary standards to the SI-second on the geoid" while the frequency of GST is adjusted to UTC.

The realization of GST(MC) produced by the backup PTF is steered to the master one. Thus, both the master and the backup GST(MC) can be considered as realizations of the SI second.

4.3.2. Orbit determination and clock synchronization

Satellite orbit determination and clock synchronization are implemented by the Galileo Orbitography and Synchronisation Processing Facility (OSPF).

The processing makes use of the pseudorange measurements collected by a global network of Galileo Sensor Stations (GSSs).

The OSPF algorithm implements the following relativistic corrections:

- Shapiro correction to the pseudorange observations;
- Relativistic correction to satellite acceleration.

OSPF performs modelling of pseudorange measurements in the ICRF system. The geometric range d is modelled by iterations:

$$d_{n+1} = \|\mathbf{r}_{GSS}(\tau - b_{GSS}) - \mathbf{r}_{sat}(\tau - b_{GSS} - \frac{d_n + \Delta}{c})\| \tag{14}$$

where:

τ is the reception time (as given by the GSS clock);
$\mathbf{r}_{GSS}(t)$ is the GSS position at the given time;
$\mathbf{r}_{sat}(t)$ is the satellite position at the given time;
b_{GSS} is the GSS clock bias;
$\Delta = D_{tropo} + \Delta t_s$
with:
D_{tropo} is the tropospheric delay;
Δt_s is the relativistic correction to the travel time (Shapiro correction).

The pseudorange measurement is then modelled as:

$$p = d + \Delta + \Delta t_r + b_{GSS} - b_{sat} \tag{15}$$

where b_{sat} is the satellite clock bias.

In OSPF a formula for Δt_r alternative to that in the ICD [3] is used:

$$\Delta t_r = \frac{2\mathbf{r}\cdot\mathbf{v}}{c^2} \tag{16}$$

Eq. (16) is derived from Eq. (5), see [1].

The Shapiro correction Δt_s is computed following Eq. (12).

As the pseudorange modeling is performed in the ICRF frame, the station coordinate vector $\mathbf{r}_{GTRF}$ (originally expressed in GTRF) needs to be transformed into ICRF:

$$\mathbf{r}_{ICRF} = ERM \cdot \mathbf{r}_{GTRF} \tag{17}$$

where ERM is the conventional Earth rotation matrix.

Since the computations are performed in ICRF, Sagnac correction does not need to be taken into account.

In the model of the satellite behavior, the OSPF algorithm applies a correction term to the satellite's acceleration in the inertial reference system according to the General Relativity Theory:

$$\mathbf{a}_{rel} = \frac{GM_E}{c^2 r^3}\left[\left(4\frac{GM_E}{r} - v^2\right)\cdot\mathbf{r} + 4\Big(\mathbf{r}\cdot\mathbf{v}\Big)\mathbf{v}\right] \tag{18}$$

where $\mathbf{r}, \mathbf{v}$ are satellite position and velocity respectively.

5. Conclusions

In this paper the major relativistic effects in satellite navigation and their treatment in Galileo were reviewed.

The relativistic effects on the Galileo satellite clocks were validated in the GIOVE mission with very high accuracy.

All important effects are either taken into account in the system design (up to the millimeter level) or will be accounted for by the user receivers.

The frequency of the Galileo satellite clocks is not corrected for the relativistic frequency shift (though, technically such correction can be applied), unlike in GPS and GLONASS. However, for operational needs, the clocks the phase and frequency offset of the satellite clocks with respect to GST is maintained within pre-defined limits. The residual relativistic relativistic effects and clock errors are absorbed in the broadcast satellite clock model allowing Galileo to deliver excellent navigation and timing performance.

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