Relativistic Corrections for the Galileo Navigation System: Operational Aspects.

The following article gives a little introduction on the relativistic effects on navigation satellites and tries to shed some light on the operational aspects of controlling and maintaining the integrity of the system. The operational aspects were discussed with Alexander Mudrak, Timing Performance Engineer at the ESA Galileo Project Office.
The general description of the relativistic effects were copied from the paper "Relativistic Effects on Satellite Navigation", Željko Hećimović [1].

Introduction

Development of satellite measurement techniques and increasing sensor-sensitivity technologies made relativistic effects significant. To use atomic clocks on Space Vehicles (SV) to test Einstein's theory of relativity was proposed already in 1955 by Friedwardt Winterberg [2].
In one of the general navigation principles, a receiver records arrival times of the pulses from more than one signal transmitter and calculates the position. When earth-orbiting satellites are used as the signal transmission sources, relativistic effects can be up to 12 kilometers after one day [3]

Sources of relativistic effects on GNSS

The main sources of relativistic effects on Global Navigation Satellite Systems (GNSS) are relative motion between the satellite and the receiver, potential differences between the satellite and the receiver, and rotation of the Earth. The main relativistic effects on satellite navigation are [4, 5]:

- Time dilation
- Time differences because of differences of the gravity field
- Relativistic effects on frequency
- Relativistic path range effects
- Relativistic Earth rotation effects
- Relativistic effects due to the orbit eccentricity
- Acceleration of the satellite in the theory of relativity.

There are more relativistic effects, but most of them are too small to be significant in satellite navigation [6].

Operational Aspects

The following discussion was conducted by SpaceOps News (SoN) via e-mail with Alexander Mudrak, ESA.
Alexander Mudrak received his Dr.-Ing. degree at the University of the German Armed Forces (Munich, Germany) in 2008. He works on the satellite navigation since 1999 including 8 years as a researcher at the German Aerospace Center. Since 2008 he works as the Timing Performance Engineer at the ESA Galileo Project Office.

The following operational aspects were discussed:

Who is responsible for the control (and possible maintenance) of the frequency compensation during operations?

Galileo System Time (GST) is the internal time reference of the Galileo system, i.e. it is used for synchronization of the elements of the Galileo Ground Segment and the satellites clocks as well as prediction of the satellite clock phase and frequency. These predictions are included into the navigation message broadcast by the Galileo satellites that enables precise user navigation and timing. GST is established by the Galileo system autonomously from other time scales and following the international recommendations. It is a continuous coordinate timescale in a geocentric reference frame steered towards Coordinated Universal Time (UTC) modulo 1 second.

UTC is maintained by the Bureau International des Poids et Mesures (BIPM). It is the time scale that forms the basis for the coordinated dissemination of standard frequencies and time signals. The UTC scale is adjusted by the insertion of leap seconds to ensure approximate agreement with the time derived from the rotation of the Earth. These leap seconds are inserted on the advice of the International Earth

Rotation and Reference Systems Service (IERS).
The physical representation of GST is generated by the Galileo Precise Time Facility (PTF). There are two PTFs. One is located in the Galileo Control Center (GCC) in Fucino (Italy) and another one is located in the GCC in Oberpfaffenhofen (Germany). Each PTF is equipped with the ensemble of atomic clocks comprising 2 active hydrogen masers (in the master - hot backup configuration) and 4 Cesium clocks. The physical output of the master hydrogen maser is steered to UTC giving the physical GST representation which is distributed within the GCC and to the remote Galileo elements.
Galileo Time Service Provider (TSP) is responsible for the determination and prediction of the GST-UTC offset and for steering of GST to UTC. TSP provides to the Galileo Ground Segment (GMS) the GST frequency steering correction on a daily basis. This correction is applied by the GMS operators as a configuration parameter which steers the maser output accordingly after its appropriate validation.
Each of the Galileo satellites carries four atomic clocks on-board (two Rubidium frequency standards (RAFS) and two passive Hydrogen masters (SPHM). Based on these clocks, each satellite generates a local frequency reference and drives the local representation of GST (LGST). LGST is initially steered to GST and the LGST-GST offset is maintained within a specified range (in order of milliseconds) by steering the payload frequency reference. The steering is applied by the Ground Control Segment (GCS) operator.

According to Table II of the paper “Relativistic Corrections in Galileo” [7] relativistic effects on the Galileo clock are not corrected by off-setting the on board clock (like on GPS). Is this still true?
GPS SIS ICD (IS-GPS-200H) explicitly states that GPS satellite clocks are corrected for the relativistic effects:
The Space Vehicle (SV) carrier frequency and clock rates -- as they would appear to an observer located in the SV -- are offset to compensate for relativistic effects. The clock rates are offset by Δ f/f = -4.4647E-10, equivalent to a change in the P-code chipping rate of 10.23 MHz offset by Δf = -4.5674E-3 Hz. This is equal to 10.2299999954326 MHz. The nominal carrier frequencies (f_0) shall be 1575.42 MHz, and 1227.6 MHz for L1 and L2, respectively.

What is actually corrected is the constant term corresponding to the circular orbit. The periodic term due to the orbit eccentricity is corrected by the user. The corresponding formula ("relativistic correction") is also given in the SIS ICD:

“20.3.3.3.3.1 User Algorithm for SV Clock Correction.

The polynomial defined in the following allows the user to determine the effective SV PRN code phase offset referenced to the phase center of the antennas (Δtsv) with respect to GPS system time (t) at the time of data transmission. The coefficients transmitted in subframe 1 describe the offset apparent to the two-frequency user for the interval of time in which the parameters are transmitted. This estimated correction accounts for the deterministic SV clock error characteristics of bias, drift and aging, as well as for the SV implementation characteristics of group delay bias and mean differential group delay. Since these coefficients do not include corrections for relativistic effects, the user's equipment must determine the requisite relativistic correction. Accordingly, the offset given below includes a term to perform this function.

The SV PRN code phase offset is given by

$$\Delta t_{sv} = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \Delta t_r \quad (2)$$

where

a_{f0}, a_{f1} and a_{f2} are the polynomial coefficients given in subframe 1, t_{oc} is the clock data reference time in seconds (reference paragraph 20.3.4.5), and Δt_r is the relativistic correction term (seconds) which is given by

$$\Delta t_r = F\, e \sqrt{A} \sin E_k.$$

(End of ICD quotation)"

Galileo OS SIS ICD does not make a statement on correction of the constant relativistic term, although, eventually, it may be done. Like in GPS, in Galileo the satellite clock is given by the second order polynomial

Galileo clock correction parameters as defined in the relevant chapters (draft project documentation):

5.1.3. Clock Correction Parameters

The clock correction parameters are transmitted according to the values stated in Table 60.

Parameter	Definition	Bits	Scale factor	Unit
t_{0c}	Clock correction data reference Time of Week	14	60	s
a_{f0}	SV clock bias correction coefficient	31*	2^{-34}	s
a_{f1}	SV clock drift correction coefficient	21*	2^{-46}	s/s
a_{f2}	SV clock drift rate correction coefficient	6*	2^{-59}	s/s^2
Total Clock Correction Size		**72**		

Table 60. Galileo Clock Correction Parameters

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB.

The model parameters are estimated by the Galileo Ground Mission Segment from satellite observations collected by the network of Galileo Sensor Stations. Without adjustment of the satellite frequency for the relativistic bias, the estimated clock model corrects also this bias - it is absorbed in the total apparent frequency offset of the satellite clock given by af1. Alike GPS, Galileo users shall correct the periodic part of the effect:

This satellite time correction (in seconds) is modelled through the following second order polynomial:

$$\Delta t_{SV}(X) = a_{f0}(X) + a_{f1}(X)[t - t_{0c}(X)] + a_{f2}(X)[t - t_{0c}(X)]^2 + \Delta t_r \qquad \text{Eq. 13}$$

where

- $a_{f0}(X)$, $a_{f1}(X)$, and $a_{f2}(X)$ are defined in 5.1.3
- $t_{0c}(X)$ is the reference time for the clock correction as defined in 5.1.3
- t is the GST time in seconds
- Δt_r, expressed in seconds, is a relativistic correction term, given by

$$\Delta t_r = F\, e\, A^{1/2} \sin(E)$$

with the orbital parameters (e, $A^{1/2}$, E) as described in paragraph 5.1.1 and

$$F = -2\mu^{1/2}/c^2 = -4.442807309 \times 10^{-10}\ s/m^{1/2}$$

With the understanding that the detailed compensation calculations is left to the User:
how is the user interface (Control Center -- User)?

Galileo satellite clocks are physically synchronized to GST in the order of milliseconds. The residual offset is computed by the GMS from satellite observations and modelled as a second order polynomial. This model is included into the Galileo navigation message broadcast to the Galileo Users by each of the satellites. The TSP predicts the GST-UTC offset. The corresponding model is also included into the navigation message. The satellite signals and the message content are described in the Galileo Open Service Signal in Space Interface Control Document released for public by the EC. User receiver applies the clock offset models as a part of the data processing.

Are any kind of interfaces used with the EGNOS system for this purpose?.

As a part of the EGNOS evolution, the capability to independently determine Galileo satellite clock corrections will be implemented in EGNOS V3. This function will make use of the EGNOS network of the monitoring stations (RIMS). I am not aware about a direct interface between the Galileo and EGNOS infrastructure for this purpose.

References

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