CONSIDERATIONS FOR THE CONCEPT OF GALILEO'S TIMEKEEPING SYSTEM

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Abstract

Satellite-based navigation would be impossible without synchronization of the system-inherent clocks. Obviously one can find high-accurate precision standards (cesium or rubidium standards) onboard the satellites and in the overall ground segment (cesium standards + H-masers). The paper outlines some basic considerations for the conception of the timekeeping system of the Galileo satellite navigation system to be new developed. This European contribution towards a 2^nd generation satellite navigation system (GNSS2) is required to be compatible and interoperable with GPS, but independent of it. These features have to be considered in the overall planning just from the beginning.

The paper reflects some architecture aspects as the number of Galileo satellites, as well as clock types which are foreseen. One of two implementation strategies on this way has to be selected for the system time: a Master or Composite Clock, the latter having some certain advantages. Due to international recommendations the new Galileo-time has to be in close agreement with UTC what requires a steering procedure. The offset versus UTC has to be broadcast to the users by means of the navigation message. For the system provider this offset is requested too. The objective for Galileo is to implement an at least equivalent or better timekeeping system compared to GPS to allow for a comparison with the present worldwide accepted GPS-standard. Some ideas for collaborations are discussed. It is well understood that the system time development is a great challenge for the European designers. The paper aims to give some insight in the present planning of Galileo to the world-wide concerned timing community and invites inputs to be given to the European system design team.

The content of this paper reflects solely the author's personal opinion.

INTRODUCTION

Presently, Europe is on the way to concept its own contribution towards GNSS2 with the satellite navigation system Galileo [1]. The key function of such a system is composed by clocks, i.e. ultra-stable frequency sources which exist in several types and are widely employed by the conventional systems GPS and GLONASS in the space and in the ground network. Navigation and timing users depend mainly on these clocks; the navigation signal is even generated on the clocks signal. To enable a solution of the navigation equation, the system provider needs to mutually synchronize all the system clocks very accurately. Such a task must be addressed in the conception of a new system like Galileo. Consequently, a new System Time Scale (STS) has to be generated.

WHAT IS GALILEO ?

The information and nomenclature outlined in this paragraph had been mainly gathered from [2] if not marked otherwise. Other details can be also obtained from [3]. All this should reflect the state-of-the-art in the development, thus, how the Galileo system could probably look like.

THE PROGRAM

With [1] the European Union's Commission (EC) made a strong recommendation on the European-led development of a constellation of new civil navigation satellites. This recommendation has to be seen as the result of a wide decision process involving an unprecedented number of experts. An essential source for the generation of technical and programmatic information is the "Comparative System Study." Under contract of the European Space Agency (ESA) four main European space companies[1] together with some 15 subcontractors performed in-depth investigations of technical, financial, and programmatic aspects for a possible European contribution to the future GNSS. So-called strategic industrial partners from USA, Russia, and Japan complement the study team.

The European approach for the next generation of GNSS is based on an open system architecture comprising of the two sub-constellations GPS IIF and a new European-led satellite navigation system called Galileo.

The navigation signals are tailored to the different service requirements, and thus, the system will provide an

- Open Access Service (OAS), and
- Controlled Access Services (CAS).

The OAS will be compatible with the GPS IIF public service. It is available to everybody worldwide and free of charge, the CAS proving that their use will be controlled by the provider(s) or operator(s). As a design goal for the CAS service, the joint sub-constellations, i.e. GPS and Galileo, shall be able to fulfil requirements for sole means of navigation for aviation.

REQUIREMENTS

The high level service requirements for Galileo can be grouped as follows:

- global overage with global positioning and timing service,
- position-related communication service,

[1] Alcatel Space Industries (ASPI), Alenia Aerospazio (ALS), DaimlerChrysler Aerospace's Dornier Satellitensysteme (DSS), Matra Marconi Space (MMS)

- OAS for mass market and in parallel CAS with guaranteed availability and accuracy for security- and safety-related applications,
- performance of the basic system shall be similar to future GPS IIF performance,
- full compatibility and interoperability with GPS.

In [2] the Galileo service requirements (so called performance A and B) are grouped for a

- Galileo global segment,
- Galileo global segment + regional segments,
- Galileo global segment + regional segments + local.

A global ground segment (see below) will guarantee the integrity requirement.

SATELLITE CONSTELLATION

The Galileo system is supposed to operate on a global basis. This resulted in the need to go for a constellation based on satellites in medium earth orbits (MEO).

Option 1:

- a "MEO only" system with 30 satellites distributed in three planes in an altitude of about 23.200 km and with an inclination of about 54 degrees

However, it has to be taken into account that the "regional performances" (see above) have to be provided for all global land masses at least. One solution then, is related to understand "region" as a "wide area" as thus, providing the regional segment's performance by using a wide area system comparable to the Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay System (EGNOS). Thus, enabling the use of geostationary satellites (GEO) as transmitters.

Option 2:

- a baseline "MEO + GEO" constellation consisting of 24 MEO and 9 GEO. The orbital altitude of the MEO will be 24126 km with an inclination of 52.5°.

The MEO will orbit in three planes in a Walker 24/3/2 constellation. The 9 GEO are grouped in 3 satellites per earth region. The satellites in one region have a spacing in longitude of 45°.

GROUND SEGMENT - 2 OPTIONS

"MEO ONLY" OPTION

In the "MEO only" option the global segment will consist of a certain number of globally distributed Orbit and Synchronization Stations (OSS). The measurement data gathered at these stations are transferred for processing to the Orbit and Synchronization Processing Facilities (OSPF) or Navigation Control Centers (NCC). The OSPF and NCC are co-located at the European Galileo Operational Centers (GOC).

> The Galileo-system time (see below) will be generated by the OSPF and will make use of all the clocks at the OSS, MEO, and clock ensembles at the European GOC.

The different parts of the navigation message are uploaded at different intervals to the satellites via the globally distributed upload stations (ULS). Monitoring and commanding of the satellites and its payload is performed in the Satellite Control center (SCC). A Navigation Management Center (NMC) is controlling the SCC and NCC. Associated with the NMC is the Galileo Support Facility (GSF) for all the business of the navigation mission that is not scheduled on a regular basis. At least, there is a Galileo Management Entity (GME) responsible for long-term technical, political, and revenue-generating decisions.

From the number of GOC, the non-European GOC host just an ULS and Galileo Uplink Interface (GUI); the European GOC consist additionally of the SCC, NCC, and OSPF of the global segment and some elements of the regional systems.

The regional system is based on the concept of integrity as a regional one. With the centralized integrity concept, all measurements taken at the integrity monitoring stations (IMS) have to be collected at the central Integrity Processing Facilities (IPF). There will be IMS nearly covering the entire globe to provide integrity over Europe. The IPF for the European region will be collocated with the ULS at the European GOC. The uplink of the regional integrity information will be performed using the ULS of the global segment. The region has to deliver the integrity information matrix at the site of the uplink station by means of the regional uplink interface (RUI).

"MEO + GEO" OPTION

The ground segment of the global segment is the same as for the "MEO only" case. In the regional system each region has to serve its own satellite constellation (at least 3 GEO). The GEO have to provide integrity information and a ranging signal for navigation with the associated navigation message. It seems necessary to replicate all the elements of the global architecture in the regional system.

> The functionality of the system time generation in the Regional Orbit and Synchronization Processing Facility (ROSPF) is different from the time generation in the OSPF. In the ROSPF the Galileo-time has to be restituted from the MEO navigation signal and the clock corrections for the GEO, ROSS, and IMS have to be computed.

One big advantage of the MEO + GEO solution would be the further provision of the EGNOS service by Galileo-satellites (the GEO ones!).

FREQUENCIES

The frequency ranges under consideration include both the lower / upper L-bands and the C-band. Dual band transmission is foreseen in L-band to compensate for the ionospheric group delay error. Combinations of signals will provide the capability for the different Galileo services.

WHY A TIME SCALE FOR GALILEO ?

The existence of a system reference time scale is compulsory for Galileo. This is due to navigation, dating, and dissemination purposes. The clocks of all the MEO-satellites and concerned ground stations (OSS, GOC) shall then be synchronized to the common system time scale (STS). This is necessary in particular for [4]:

- providing a correct information on the clock status in the navigation message as the basis for a correct solution of the user's navigation equation,
- evaluating satellite ephemeris,
- having a common reference time for scheduled activities, for example performing synchronization measurements in the system,
- disseminating a reference time scale or Universal Time Coordinated (UTC) to different users.

The STS can be an (almost) independent time scale with the unique request of being the common reference for the overall navigation system. There is also a need for

- an optimization for a certain integration time (short-, medium-, long-term) depending on the system concept,
- achieving a high level of accuracy for time dissemination purposes by means of a steering towards UTC.

The update of the clock parameters is influenced by the orbital satellite-to-ground constellation. The access delay of the STS has to be accounted for. But this also means that stability of STS is of utmost importance.

SYSTEM TIME ARCHITECTURE

BASIC CONSIDERATIONS

Mutual synchronization of all the system clocks is required, thus a STS is needed. This STS has to be reliable, stable, and efficient in its generation. From [1] it can be concluded that STS has to be independent on another navigation system's time.

International recommendations request a steering of Galileo-STS towards UTC. UTC is the ultimate reference time computed at the BIPM by about 50 laboratories distributed worldwide including approximately 200 clocks. Due to the choice of optimizing its long-term stability and also for practical reasons, UTC exists only "after the fact," and results are available with a delay of one month. Therefore, many local approximate realizations were created and the Galileo system time, steered towards UTC, could be also a mean for disseminating UTC in almost real-time around the world.

Additionally, a former CCDS recommendations requires that

the reference times (modulo 1 s) of satellite navigation systems with global coverage have to be synchronized as closely as possible to UTC.

Now, the CCTF came out within its 1999 recommendation:

all global navigation satellite systems to be designed so that it is possible to use their signals for time and frequency comparisons.

The existence of a cheap and accurate reference time scale with easy access is requested by telecommunication institutions, scientific laboratories, and astronomical observatories, industries that synchronize their computers, banks, watch sellers, transportation systems etc.. This clearly asks for a close agreement versus UTC and the Galileo-system time must ensure the best metrological qualities in the mean time, when UTC is not known. This is a reason suggesting that the Galileo-system time should be optimized over an integration interval of about 10 - 20 days.

It should be pointed out that UTC is also required to determine the orientation of the earth in space, leading to another argument why the Galileo-system time must be accurately related to UTC. Without that navigation and positioning on the earth would not even be possible.

Galileo must make use of an "inside" or "outside" real-time UTC-source. This could be a well established timing lab which realizes a local real-time UTC(*k*)-scale, where *k* is the designation of the timing lab. There are both technical and institutional issues when trying to connect UTC(*k*) to the outside world, and these need to be resolved. The preliminary view is that good cesium clocks will be needed, although another view is that a clock ensemble could be used to achieve the requirements. H-masers might be the best approach to the connection between UTC(*k*) and Galileo-system time.

A UTC-source "inside" the Operational Control Segment (OCS) would mean the best technical solution. One of the European ground clocks in a GOC which represents UTC(*k*) contributes to UTC. In case it is "outside" a link to the OCS has to be established from time to time by means of "Common-Views" or 2-way link (similar to GPS, i.e. USNO(MC2) versus USNO(AMC1)). The final method still hasn't be selected. It is proposed that the European timing labs will have to take part on the discussions towards technical solutions, because most of the relevant experience is located here.

The institutional selection of a certain UTC(*k*)-source for Galileo still did not started, but could include:

- internationally accepted labs
- institutions directly concerned with navigation
- a new established organization.

The selected institution must be made liable for this service!

It has to be stated that UTC(USNO) is the best real-time estimation of UTC! GPS takes advantage of this attribute.

STS APPROACH

In general, the STS can be generated as a [4]

- Master Clock or an
- Ensemble Clock.

For Galileo an Ensemble Clock (Composite Clock) based on all MEO, OSS, and European GOC clocks is supposed to be realized. Thus, the STS is based on the global system only. The new Galileo-STS will be generated at the OSPF independently of GPS ! From this follows that a large number of clocks is supposed to be operated in the global ground segment, and some clock ensembles at certain ground stations (European GOC), see below. In [2] it is told that only 1-way measurement signals will be used. Anyhow, it is recommended to include also high accurate 2-way data in the overall processing for different purposes.

CONSIDERED CLOCK TYPES

Onboard the MEO satellites Rubidium Atomic Frequency Standards (RAFS) are considered to be installed. Each MEO satellite will probably carry 3 RAFS. Only one clock is actively operating, the others being in redundancy. The foreseen RAFS is in its final phase of development under an ESA contract at TNT (Temex Neuchatel Time SA).

	Frequency Stability (Allan Variance)		
	Space Rubidium Clock		Space H-Maser
Interval	US	Europe	only European
	(approx.)		
10 s	$2.0\cdot10^{-12}$	$1.6\cdot10^{-12}$	$2.1\cdot10^{-14}$
100 s	$5.0\cdot10^{-13}$	$5.0\cdot10^{-13}$	$5.1\cdot10^{-15}$
1000 s	$2.0\cdot10^{-13}$	$1.6\cdot10^{-13}$	$2.1\cdot10^{-15}$
10000 s	$5.5\cdot10^{-14}$	$5.0\cdot10^{-14}$	$1.5\cdot10^{-15}$
100000 s	$1.5\cdot10^{-14}$	$5.0\cdot10^{-14}$	n.a.

Tab. 2: Stability specifications of some space clocks

In ground (OSS) high-performance cesium standards can be expected. For redundancy purposes two clocks per OSS should be installed in a suitable environment. The European GOC handle a clock ensemble with high-performance cesium clocks complemented by H-masers.

COLLABORATION WITH GPS

To satisfy the requirement of Galileo of being independent of any other navigation system, the Galileo system time has to be independent too. In GPS the corresponding time scale is obtained from the Master

Kalman filter where both the satellite orbits and satellite & ground clock corrections are obtained. Thus, Galileo has to follow this approach and define as well as design its own time scale.

For interoperability and compatibility purposes, for instance with GPS, a close agreement to GPS-time should be addressed. Considering the fact that the Galileo-system time will be steered to UTC (see above), and thus be handled in a same manner as GPS-time, the close agreement can be achieved more or less "automatically."

Thus, a difference will exist in a first approach, but some efforts can be taken to minimize it. To allow the user to use both systems, the estimated time difference between both systems should be included in the navigation message. Thus, in situations where only a limited number of satellites is visible (urban areas) the user can benefit from an increased number of satellites, as the "other" system can be applied too.

Topics

Based on the above ideas the following proposals can be made:

- Once the Galileo system time has been synchronized with GPS-time, the offset between both time scales should be transmitted by the Galileo satellites.
- The new requirement for the difference GPS-time - UTC(USNO) is to be within 20 ns. This figure should also be met by Galileo.
- A permanent 2-way link or "Common-View" between UTC(USNO) or AMC1 and the selected UTC(*k*) can be proposed.
- A Galileo Monitor Station (MS) could be co-located in the GPS OCS; the same could be established for a GPS MS in the Galileo OCS. The goal is to have at least a "common" clock in both systems OCS to support the steering of both time scales to be close to each other and towards UTC.
- At least at one Galileo satellite a specific navigation transponder for two-way time comparison purposes could be implemented. In this way up to now undetected biases could be eliminated, being of highest interest for the global timing community. The Galileo OCS could take advantage from this too (more accurate clock comparisons, etc.)
- The ground clocks of the OCS hosted in stable environment conditions could be applied for UTC computation by the BIPM. This should essentially support the GSTS-steering process towards UTC.

CONCLUSION

The paper outlined the present proposal for the Galileo concept and reflects a discussion on the baseline for the Galileo-system time. The mutual synchronization of the system clocks is required. This will be realized within a well design time keeping system generating a Galileo-system time. This system time has to be reliable, stable, and cost-efficient in its generation, but it has to be independent of GPS-time! International recommendations request a steering of the Galileo system time towards UTC. For GPS/Galileo interoperability purposes the Galileo-system time has to be synchronized to GPS-time.

In the Galileo navigation message content we should find:

- clock correction parameters versus Galileo-system time (offset, rate, drift)
- the difference of Galileo-system time versus a real-time realization of UTC and TAI
- a prediction of the difference of Galileo-system time versus UTC and TAI, as well as GPS time

It is accepted worldwide that GPS time is a high-performance system time. For GPS and for world-wide time & frequency distribution UTC(USNO) is the external UTC-source. This is a high performing time scale and closest real-time UTC realization available presently. It is well noted that for Galileo to reach the same level of overall timing performance is a great challenge!

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