TIME DISSEMINATION AND COMMON VIEW TIME TRANSFER WITH GALILEO: HOW ACCURATE WILL IT BE?

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Abstract

The future European navigation system Galileo will provide both positioning and timing capabilities to its users in the frame of four basic navigation services. Two of them are of special interest: the Safety-of-Life (SoL) Service that will be associated with certain performance guarantees, and the Open Service that will be provided free of charge.

In this paper, we assess the average accuracy of user synchronization to the Galileo system time using a prospective Galileo error budget and simulations of the Galileo satellite constellation. These simulations also allowed us to transform the (guaranteed) positioning performance of Galileo's SoL Service into the timing domain, and, thus, to identify the guarantees for timing users of this service. For comparison purposes, the timing accuracy of GPS – considering its actual and projected error budget – is shown.

We also demonstrate the performance of four selected processing techniques – an optimally unbiased moving average, an adaptive linear enhancer, a Kalman filter, and a smoother – applied to Galileo Common View data that were simulated with the help of DLR's GNSS simulation tool NavSim.

INTRODUCTION

Presently GPS is widely used for timing applications both in stand-alone (ground clock being synchronized to GPS system time) or differential (ground clock being synchronized to another ground clock) modes. GPS-based techniques provide accuracy at a nanosecond to sub-nanosecond level, but are dependent on services from the system operator that are not assured to the civil user community and may be disrupted. With the projected advent of Galileo the situation may change in two ways: on the one hand, Galileo is announcing to provide a guaranteed service (the SoL service) for specific user groups, and, on the other hand, the future capability of observing simultaneously an increased number of satellites and receiving an increased number of navigation signals in different frequency bands opens the arena for investigating advanced synchronization methods making strong use of those new features.

However, before investigating the potential of methods based on the combined use of GPS and Galileo signals, one first needs to know if the performance of Galileo signals will be similar to the well-known GPS performance. Since first Galileo signals are not expected to be available until 2005, the assessment of the system capabilities prior to satellite launch should be based on simulations.

In this paper, we assess the potential Galileo performance for user synchronization in stand-alone and in

Common View modes.

GALILEO NAVIGATION SERVICES

Galileo will provide its users four basic navigation services:

- Open Service: Provides global, free-of-charge positioning, and timing capabilities by means of navigation signals separated in frequency.
- Safety-of-Life (SoL) Service: Provides integrity information by means of encrypted supplementary signals within the navigation signals of the Open Service. The performance of the SoL service will be guaranteed.
- Commercial Service: Provides additional data dissemination services and a third navigation signal with controlled access.
- Public Regulated Service: Provides global positioning and timing capabilities by means of two navigation signals separated in frequency. Access to these signals will be controlled.

Specifications of service performance and allocation of Galileo satellite signals as defined in the Galileo High Level Mission Definition Document (HLD) **[1]** are summarized in Table 1. Requirements for time synchronization accuracy are given only for static users of Open Service and only with respect to UTC. However, one may expect that a number of applications will be satisfied already with synchronization to Galileo system time (GST) as long as it is kept within 50 ns to UTC. Also, synchronization performance for users of the SoL Service is implicitly guaranteed due to its direct connection to the positioning performance. These considerations motivated us to investigate synchronization accuracy for SoL users. Also, we compared Galileo's SoL performance with GPS.

Table 1. Performance of Galileo services.

Service	**Accuracy (95%)**			
	horizontal	**vertical**	**time vs. UTC**	**relative frequency vs. UTC**
Open - single freq. - dual freq.	 15 m 4 m	 35 m 8 m	 not specified 30 ns	 not specified 3×10^{-13}
Safety-of-Life	4 m	8 m	not specified	not specified
Public Reg. - single freq. - dual freq.	 15 m 6.5 m	 35 m 12 m	 not specified not specified	 not specified not specified

ERROR BUDGET FOR GALILEO AND GPS USERS

The effective error of user pseudorange measurements *UERE* is described by the following equation (correlation of individual error sources not considered, following **[2]** and **[3]**):

$$UERE = \sqrt{\sigma_{eph+cl}^2 + \sigma_{ion}^2 + \sigma_{trop}^2 + \sigma_{mp}^2 + \sigma_{\mathrm{int}}^2 + \sigma_n^2} \quad (1)$$

Here, σ_{eph+cl}, σ_{ion}, σ_{trop}, σ_{mp}, σ_{int}, and σ_n are errors due to uncertainties of the broadcast ephemeris and clock parameters, residual (after correction) ionospheric and tropospheric effects, multipath, interference, and receiver noise respectively.

User measurement errors were analyzed during the definition phase of the Galileo program. The finalized error budget for users of the dual-frequency Open and Safety-of-Life Service is given in Table 2.

Table 2. Error budget for combination of Galileo L1 and E5b signals **[4]**.

Elevation (deg)	10	15	20	25	30	40	50	60	90
UERE (m)	1.26	1.13	1.07	1.05	1.03	1.01	1.01	1.00	1.00

GPS provides positioning and timing capabilities for civil users in the frame of its Standard Positioning Service (SPS), which is based on the navigation signal (C/A pseudorandom code and navigation message) transmitted at the L1 frequency. The timing capabilities refer to user synchronization to UTC (USNO). As defined in GPS SPS Performance Standard, it shall be better than 40 ns (95%) as far as contribution of GPS Signal-In-Space is concerned.

A conservative error budget for users of GPS Standard Positioning Service is summarized in Table 3.

Table 3. GPS error budget.

Error source	**RMS (m)**			
	1996, single freq., no SA [2]	**1996, single freq., w. SA [2]**	**2003, single freq., no SA**	**2010 (plan), dual frequency [3]**
Ephemeris data	2.1	2.1	2.8	1.2
Satellite clock	2.1	20		
Ionosphere	4	4	4	0.4
Troposphere	0.7	0.7	0.5	0.2
Multipath	1.4	1.4	1.4	0.7
Receiver noise	0.5	0.5	0.3	
Total	**5.3**	**20.6**	**5.1**	**1.5**

TIMING ACCURACY FOR GALILEO USERS

ACCURACY GUARANTEES

According to a well-known relationship (see e.g. **[2]**), instantaneous horizontal and vertical positioning errors as well as user timing errors (*HPE*, *VPE*, and *TE* respectively) can be represented as a product of the ranging error *UERE* and the Dilution Of Precision factor (DOP):

$$
\begin{aligned}
HPE\ (95\%) &= 2 \cdot UERE \cdot HDOP \qquad (m) \\
VPE\ (95\%) &= 2 \cdot UERE \cdot VDOP \qquad (m) \\
TE\ (95\%) &= 2 \cdot \frac{UERE}{c} \cdot TDOP \qquad (s)
\end{aligned} \tag{2}
$$

Galileo users will probably utilize a weighting scheme (as well as *de-facto* the majority of GPS users) that requires reconsidering computation of DOP. However, since the weighting for Galileo measurements is not yet detailed, we will work with "classical" (non-weighted) DOPs in our calculations.

Inverse application of Eq. 2 to Galileo's SoL service specification (see Table 1) considering the maximum Galileo DOP values gives the maximal value of $UERE$ that still allows meeting the specifications.

To assess DOPs, we simulated the nominal constellation of Galileo (in three planes, each with 9 equally spaced satellites) for 72 hours (the repetition period of Galileo constellation). DOP values were computed for one meridian (the constellation geometry possesses a longitude symmetry) with a 10° elevation cut-off angle. The maximal values of $HDOP$, $VDOP$, and $TDOP$ are shown in the left part of Figure 1, and number of satellites in view is presented in its right part. The global maxima of $HDOP$ and $VDOP$ are 1.55 and 3.08 respectively. The corresponding $UERE$ value is 1.3 m (from Eq. 2 and Table 1).

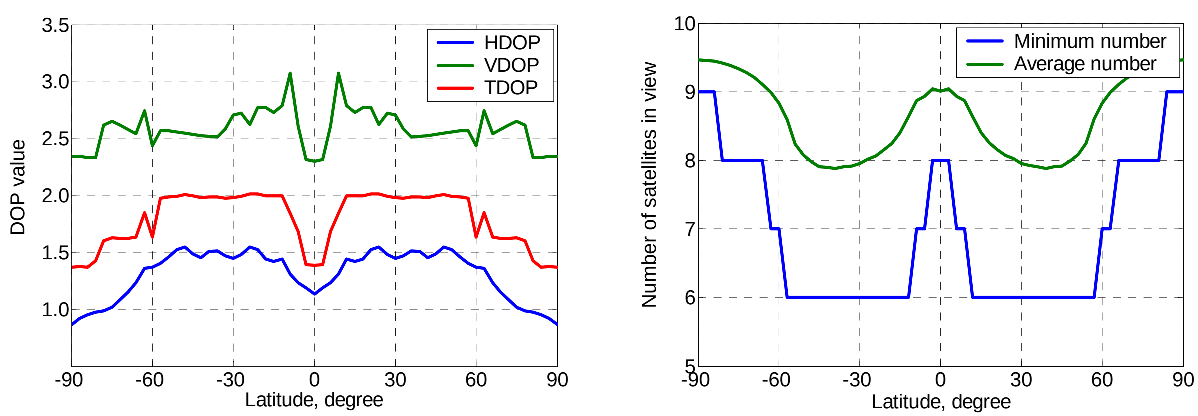


Figure 1. DOP values (left) and number of observed satellites (right) for Galileo users.

With the global $TDOP$ maximum of 2.01 and the $UERE$ estimated above (1.3 m), Eq. 2 gives 17.5 ns (95%) for the instant synchronization accuracy of user synchronization to Galileo system time. This accuracy is implicitly guaranteed for users of the SoL service. It is associated with 100% availability for the nominal constellation of Galileo and a typical user environment. This value is also inherent to the specification of the Open Service, which, however, will not provide performance guarantees.

Note that Eq. 2 overestimates the horizontal positioning error as shown in **[3]**, since it does not account for correlation between errors of user observations. For the same reason, the estimation of the timing error can appear too optimistic.

The transformation of accuracy requirements described above is valid for users who determine both their position and time. Stationary users at a known position (e.g., a time laboratory) need to estimate only their time bias, which can be computed, e.g., as an average of available observations. Thus, the snapshot accuracy of user synchronization to Galileo system time is given by

$$TE\ (95\%) = 2\frac{UERE}{c \cdot \sqrt{N}} \tag{3}$$

where N is the number of satellites in view.

To get the upper limit for the synchronization error, we used the minimal number of satellites in view (see Figure 1). Eq. 3 gives the synchronization error of about 3.5 ns (95%) for static users at known position. This estimate is optimistic, since it does not consider correlation between user measurements. However, the synchronization error will be better than error of single observation – 8.7 ns (95%) – in any case.

AVERAGE TIMING ACCURACY FOR GALILEO AND GPS USERS

To assess the average accuracy of synchronization to GST and GPS Time, we used the Galileo and GPS error budgets (Tables 2 and 3) and simulated *TDOP*. Instant *TDOP* values have been calculated by simulating both Galileo (nominal constellation) and GPS (current constellation of 28 satellites) over 72 hours for a global grid with resolution of 2 degrees. Those *TDOPs* have been averaged over the simulation span for each of the grid nodes (see Figure 2).

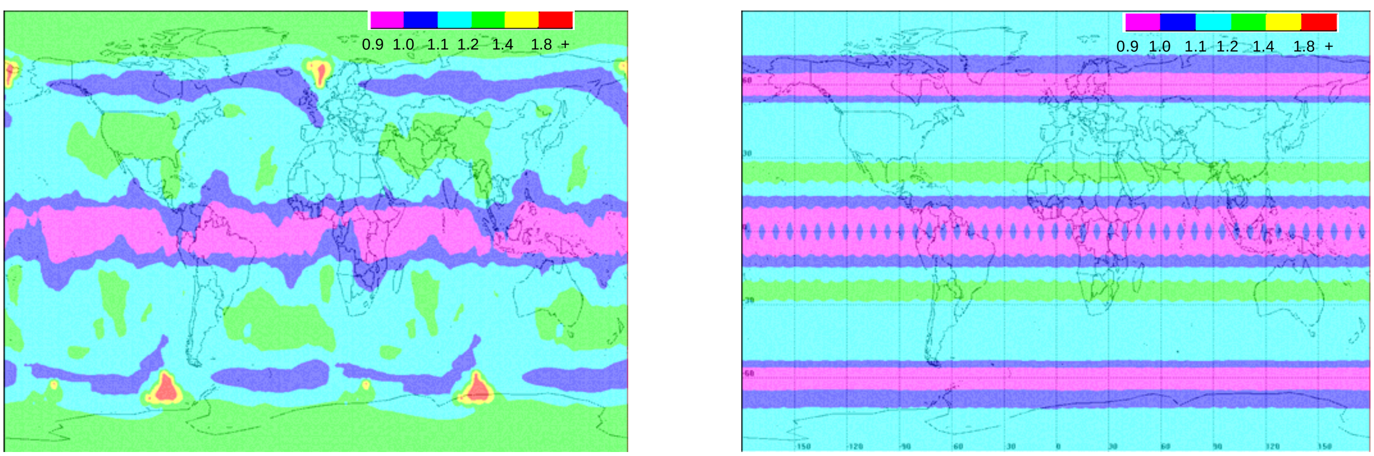


Figure 2. Average *TDOP* for GPS (left) and Galileo (right) constellations.

Multiplication of *TDOP* by *UERE* yields the average synchronization accuracy for GPS (Figure 3) and Galileo users (Figure 4). Note that the complete pictures “drift” along longitude depending on the selected reference epoch of simulations. The global average of user synchronization error (1σ, 67.8%) is 19.2 ns (present) or 5.7 ns (projected for 2010) for GPS and 3.8 ns for Galileo.

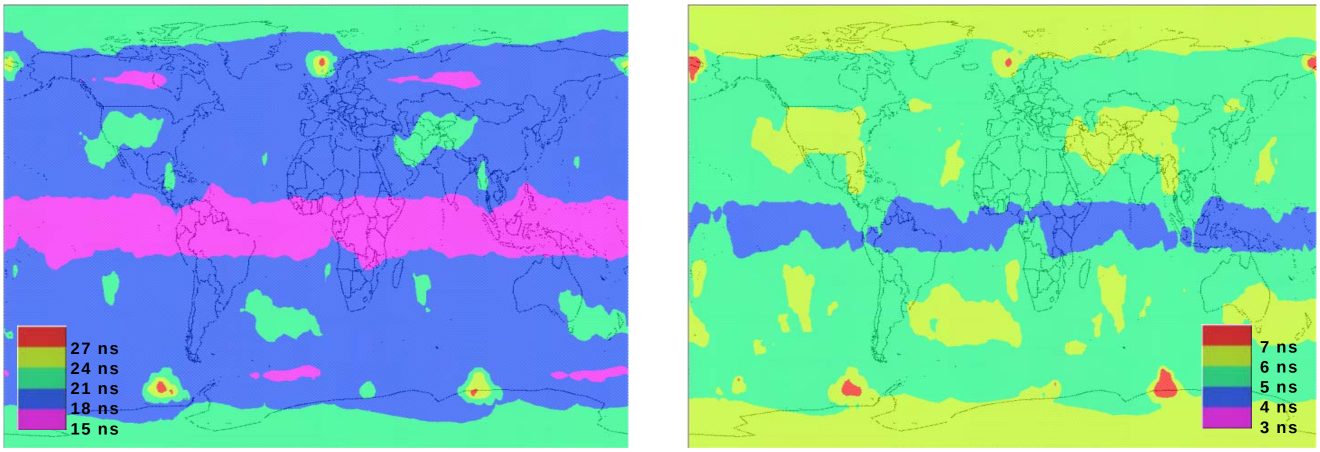


Figure 3. Average synchronization accuracy (1σ) for GPS users (present, left; projected for 2010, right).

A combined use of GPS and Galileo for stand-alone timing applications is not straightforward due to the offset between GPS Time and Galileo System Time.

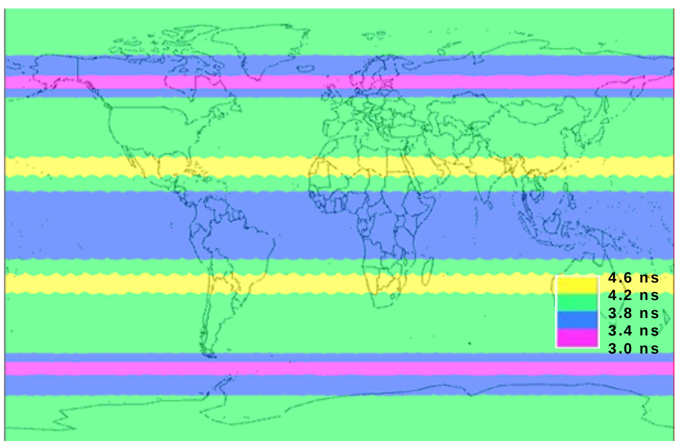


Figure 4. Average synchronization accuracy (1σ) for Galileo users.

TIME TRANSFER WITH GALILEO

COMMON VIEW WITH GALILEO

Since the eighties, time transfer based on simultaneous observations of GPS satellites by remote laboratories – Common View – has been a *de-facto* standard. Thus, BIPM employs this method to link clocks included in the computation of TAI/UTC. The "classical" Common View makes use of pseudorange measurements and allows one to reach the accuracy of a few nanoseconds after averaging over a few days. Taking into account the schedule for the first Galileo satellite in orbit (2005), it is worth considering an implementation of Common View for Galileo already now.

Important features of the "classical" GPS Common View as utilized for time transfer to TAI **[5]** are

- utilization of a tracking schedule to ensure the simultaneity of satellite observations,

- preprocessing (correction and smoothing) of "raw" pseudorange measurements in time receivers, which results in generation of data points smoothed over fixed intervals of 960 s,
- utilization of a standard format for data exchange (CGGTTS), and
- delegation of time offset computations to BIPM itself.

Recent developments in the time transfer of TAI with modified geodetic receivers – multi-channel dual frequency receivers capable of synchronization to a local clock – have led to a revision of the "classical" approach **[6]**. One of the main points of this revision is the preprocessing of satellite observations in a stand-alone software that accepts as an input RINEX, the conventional format for observation exchange in the geodetic community. Another important feature is the computation of ionospheric correction from dual-frequency observations. Finally, multi-channel receivers do not use the tracking schedule in the strict sense (what satellites at what time to track) and track simultaneously as many satellites as they can. However, observations should be referenced to a time schedule that defines reference points of 960-second intervals common for all participating receivers. Obviously, an implementation of a Common View procedure for Galileo will have to account for Galileo specifics. Two of them are discussed below.

Data Preprocessing and Smoothing Interval

According to **[5]**, the smoothing interval of 960 seconds was defined as follows: 2 minutes to lock to a GPS satellite, 12.5 minutes to receive the complete GPS navigation message, 1 minute to process the data. This calculation is not applicable for Galileo, which will ensure shorter signal acquisition time (as well as modern GPS receivers) and will have a different duration of the navigation message. The impact of the application of the 960-second smoothing intervals to Galileo data requires further studies.

An alternative approach is now feasible due to recent development of a Common View preprocessing program that can be executed outside a time receiver (e.g. on a PC) **[6]**. Thus, Common View participants may exchange RINEX data, and the pre-processing can be done in an analysis center. It will help to exclude errors associated with the use of different versions of the preprocessing software and to preserve the noise spectrum, which otherwise is distorted by the smoothing procedure.

Observation Schedule

The repeatability of Galileo constellation geometry will be about 72 hours (compare to ~ 23 h 56 min for GPS). This pattern is illustrated in Figure 5, which presents simulated elevation and azimuth of a Galileo satellite as seen from DLR site in Oberpfaffenhofen (Germany). Potential losses of Galileo observations with the current observation schedule should be further investigated.

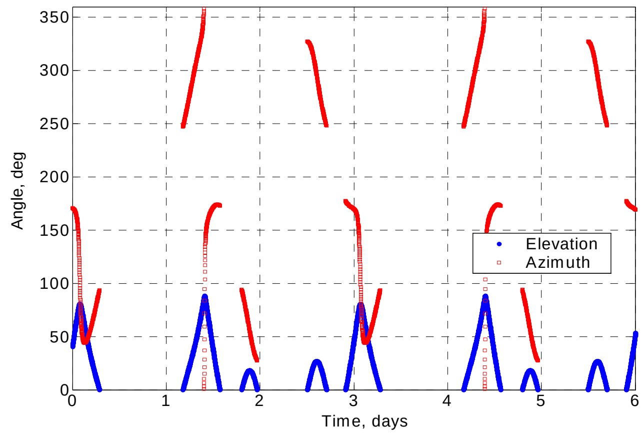


Figure 5. Visibility of a Galileo satellite: azimuth and elevation angles.

AVAILABILITY OF SATELLITES IN COMMON VIEW

To assess the capabilities of Galileo Common View in terms of simultaneously visible satellites, we have simulated two links: DLR – PTB and DLR – USNO (see Figure 6 and Table 4). Note that unlike the stand-alone time synchronization, the combination of GPS and Galileo signals can be used for Common View due to elimination of satellite clock biases in differences of pseudorange observations.

Table 4. Number of satellites in common view for the links PTB – DLR and USNO – DLR.

GNSS	**Number of satellites in common view**					
	Link PTB-DLR			**Link USNO-DLR**		
	min	**max**	**average**	**Min**	**max**	**Average**
GPS	5	11	7.6	2	6	3.6
Galileo	6	10	7.7	1	6	3.7
GPS+Galileo	12	19	15.4	4	11	7.3

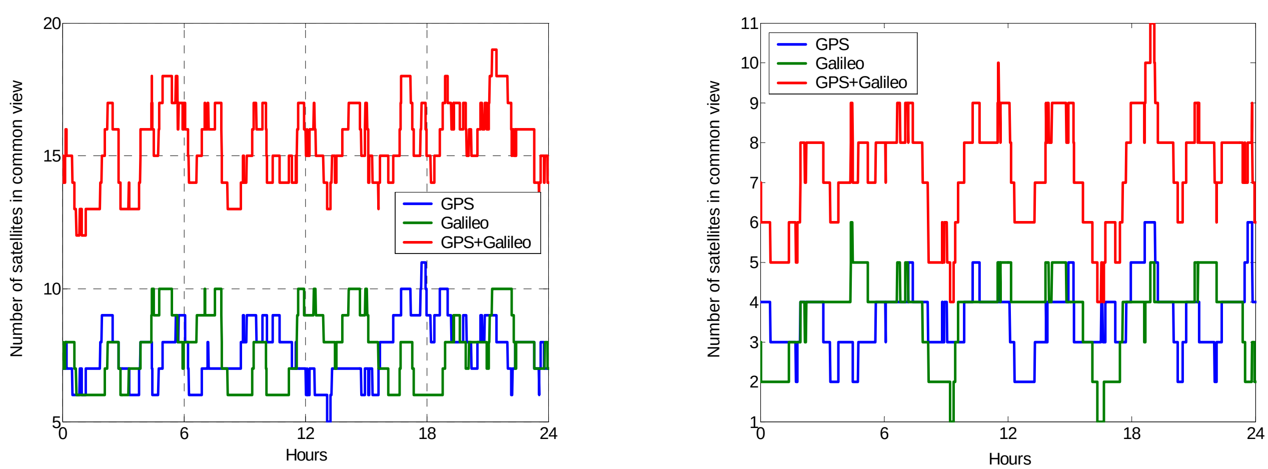


Figure 6. Number of satellites in common view between PTB and DLR (left) and USNO and DLR (right).

SIMULATION OF GALILEO COMMON VIEW

In the next step, we simulated Galileo observations (all-in-view approach) over 1 month for PTB and DLR and processed them following the modified Common View procedure **[6]** (see Figure 7). The simulation included orbit, ionospheric, tropospheric, receiver noise, and receiver clocks errors (H-maser at PTB and cesium with a conservative flicker floor of 2×10^{-14} at DLR).

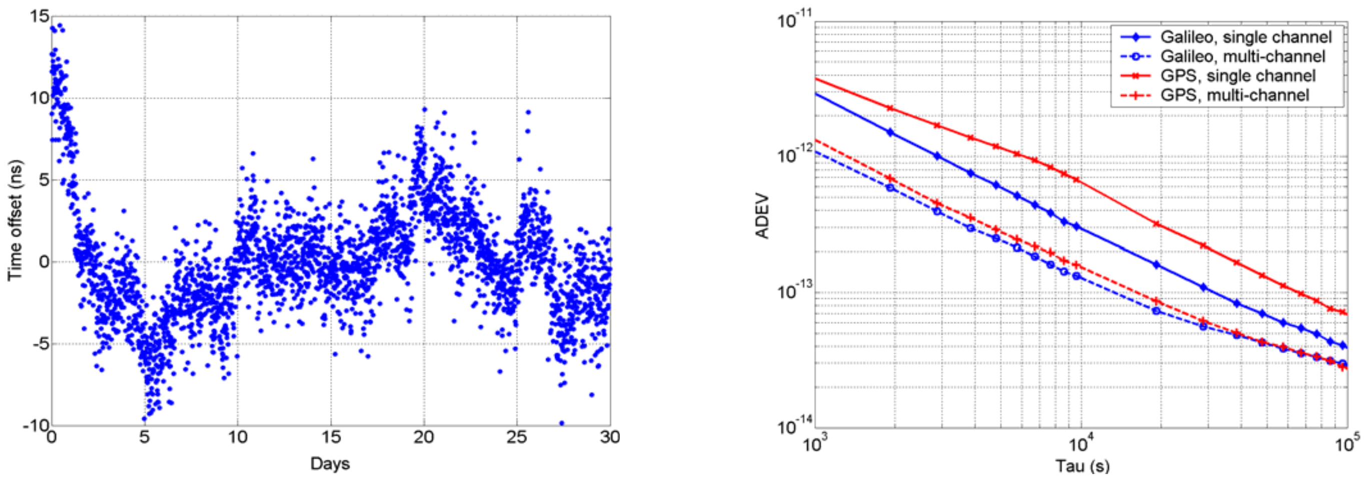


Figure 7. Simulated Galileo Common View data: time offset (left) and Allan deviation (right).

Figure 7 (right) presents the Allan deviation of Galileo Common View for both single-channel and for multi-channel Common View. The multi-channel data were computed through averaging of all single-channel results available at a certain time. For comparison purposes, the performance of GPS Common View between PTB and DLR (as computed from real GPS measurements collected in June 2003) is also shown in Figure 7. The Common View was performed according to the procedure described in **[6]**. A GPS receiver at PTB was connected to an active H-maser; a cesium clock was used at DLR. As can be seen from Figure 7, simulated multi-channel Galileo Common View exhibits only a slight improvement of accuracy with respect to GPS.

FILTERING AND SMOOTHING OF COMMON VIEW RESULTS

The accuracy of time transfer can be further improved by an additional filtering/smoothing of Common View data. Obviously, selected filtering/smoothing techniques should be customized to the problem at hand to ensure its ability to produce a representative and accurate output. However, estimation of the performance of a certain technique with real observation data often faces the problem that the true clock offset is unknown. Thus, the benefit of working with simulated data is the availability of the true clock offset. It allows one to assess not only the stability, but also the accuracy, of a filter.

Here we present a comparison of four processing techniques – an optimally unbiased moving average

(OUMA), an adaptive line enhancer (ALE), a Kalman filter, and a Kalman smoother – applied to simulated Galileo Common View data (the same data set as addressed above was used).

OPTIMALLY UNBIASED MOVING AVERAGE (OUMA)

Due to their implementation simplicity and low computation burden, moving average filters are especially suitable for real-time applications. An optimally unbiased OUMA filter is described by the following model:

$$y_n = \sum_{i=0}^{L-1} w_i z_{n-i} = \mathbf{w}^T(n)\,\mathbf{z}(n) \tag{4}$$

where y_n is the n-th filtered observation, $\mathbf{w} = [w_0 \quad w_1 \quad \dots \quad w_{L-1}]^T$ is the vector of L filter weights, $\mathbf{z}(n) = [z_n \quad z_{n-1} \quad \dots \quad z_{n-L+1}]^T$ is the vector of L last observations, and L is the filter length (averaging window). The filter weights are calculated according to **[7]**:

$$w_i = \frac{2L(2L-3)+9-6i(L-1)}{L(L^2+6)},\ 0 \le i \le L-1. \tag{5}$$

ADAPTIVE LINE ENHANCER (ALE)

Adaptive line enhancer filter is widely used in signal processing to detect periodic signals buried in a broad-band noise **[8]**. In the current application, we use the property of ALE that the filter response is matched to the spectrum of the correlated components of the input signal (in our case, Common View data). Therefore, the true clock offset, which is highly correlated, can be successfully detected and the uncorrelated part of the observation noise will be significantly suppressed. The model of ALE is given by

$$y_n = \mathbf{w}^T(n)\,\mathbf{z}(n-\Delta) \tag{6}$$

But now the weight vector $\mathbf{w}(n)$ is adapted in order to minimize the mean-squared error between the filter output y_n and a desired response that is equal to observation vector $\mathbf{z}(n)$:

$$\begin{aligned} &\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\,\mathbf{z}(n-\Delta)\cdot\mathbf{e}(n) \\ &\mathbf{e}(n) = \mathbf{z}(n) - \mathbf{y}(n) \end{aligned} \tag{7}$$

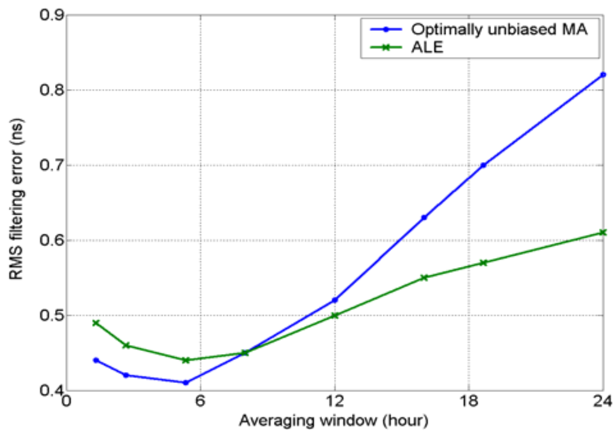
A specific feature of ALE is the use of the delayed version $\mathbf{z}(n-\Delta)$ of primary input signal $\mathbf{z}(n)$ to detect the correlated part of the input signal. The prediction delay Δ should be large enough to ensure that noise components in $\mathbf{z}(n-\Delta)$ and $\mathbf{z}(n)$ are uncorrelated. Adoption step size μ defines the relative weight of newly coming observations.

KALMAN FILTER AND SMOOTHER

A Kalman filter and smoother were implemented according to **[9]**. We used varying dimensions of observation vector corresponding to the number of satellites in common view at a certain observation epoch. The process covariance matrix $\mathbf{Q}$ was defined to match the characteristics of simulated clocks at PTB and DLR.

PERFORMANCE OF FILTERING/SMOOTHING TECHNIQUES

It is well known that the performance of both OUMA and ALE filters are extremely sensitive to the size of averaging window (prediction depth in terms of ALE) that should be selected based on characteristics of participating clocks and of observation noise. To solve this problem empirically for the simulated scenario, we processed simulated multi-channel Common View, with both methods varying the averaging window from 1.3 to 24 hours. Then we computed the difference between filter output and the known clock offset that was added to the simulated data (see Figure 8, left). The Allan deviation (ADEV) (see Figure 8, right) for both filters was also estimated.



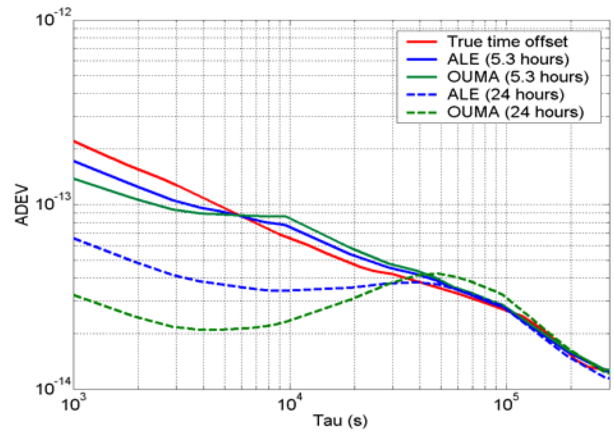


Figure 8. Optimally unbiased MA (OUMA) and ALE: filtering error (left) and Allan deviation (right).

It appears that both OUMA and ALE reach the optimal performance at the averaging window of 5.3 hours; then their performance degrades – much quicker for OUMA than for ALE – and the Allan deviation of ALE output is always higher in the short term and better in the long term than that of OUMA. This makes ALE more attractive for real-world applications. However, in our experiment the accuracy of ALE with the optimal averaging window was worse than that of OUMA. It points out the need for adjustment of ALE parameters.

As expected, the performance of the Kalman filter and smoother was superior to more simple OUMA and ALE filters. Figure 9 presents the root mean squares (rms) error (left) and the Allan deviation (right) for the Kalman filter and smoother implemented with a two-state clock model (phase and frequency) and process covariance matrix accounting for white frequency noise and frequency random walk. Equal weights were used for all satellites. Further improvement may be expected through utilization of elevation-dependent observation weights and accounting for flicker noise of clocks.

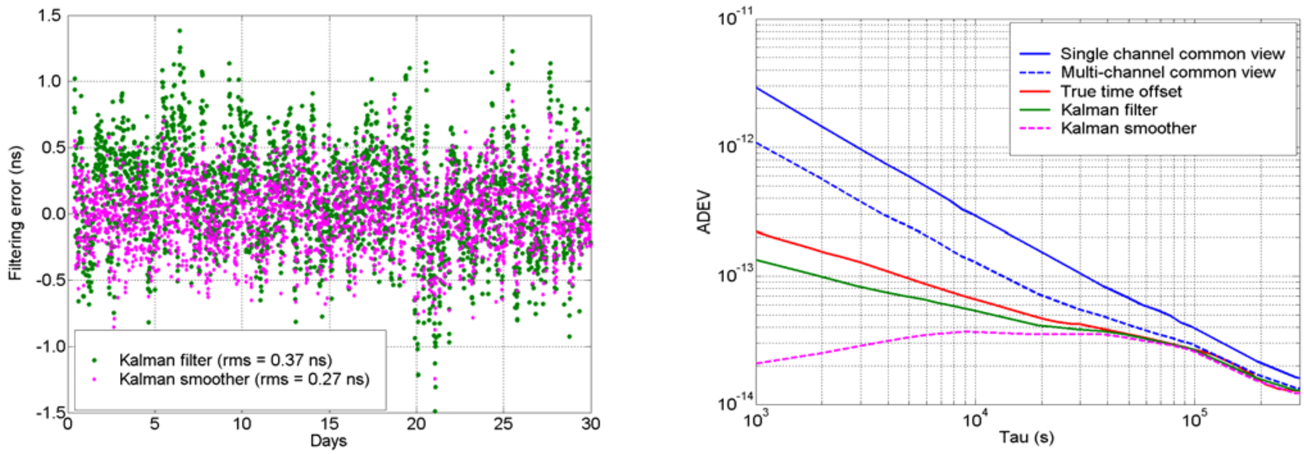


Figure 9. Kalman filter and smoother: filtering error (left) and Allan deviation (right).

Thus, ALE and the Kalman filter seem to be good candidates for real-time applications – ALE due to its relative simplicity is suitable also for hardware implementation – and the Kalman smoother demonstrates the best performance as a postprocessing technique.

CONCLUSION

Simulations of Galileo constellation geometry presented in the first part of this paper allowed us to obtain preliminary estimates of (implicitly) guaranteed and average synchronization accuracy for users of the SoL service (with respect to Galileo system time). These parameters are missing in those Galileo programmatic documents that are available for public use. However, we should comment that our results assume a simplified user algorithm (no observation weights). Also, further work is required to account for multipath errors in satellite observations.

Our simulation of Galileo Common View between DLR and PTB demonstrated a slight performance improvement compared to GPS, with the procedure implemented presently for dual-frequency geodetic receivers.

The simulated Galileo Common View data were further processed with selected filtering/smoothing techniques. The analysis of processing results allowed us to identify a potential benefit of using the adaptive line enhancer (ALE) for timing applications. However, there is a need to optimize its parameters. The performance of the Kalman filter and smoother – the latter being a very promising tool for postprocessing applications – can be further improved through implementation of proper covariance matrices for clocks and observations. Here, simulation of Galileo and GPS can be helpful, since they allow one to generate both observations and clock data with precisely known scenarios.

ACKNOWLEDGMENTS

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QUESTIONS AND ANSWERS

JUDAH LEVINE (National Institute of Standards and Technology): Could you comment on how you provide a service guarantee with respect to UTC, when UTC does not exist in real time?

JOHANN FURTHNER: This is not a guarantee service to provide UTC. It is a guaranteed service to estimate the Galileo system time.

LEVINE: Okay, when you say "UTC," most of us understand that to mean something other than Galileo system time.

FURTHNER: Galileo system time has information on how it is different from UTC. This is in the navigation message.

LEVINE: But how do you do that in real time? UTC doesn't exist.

FURTHNER: We have here situations that Galileo system time is computed in two "precise time facilities" which contain two active H-masers and four cesium clocks. A timing service provider will compute the Galileo system time to UTC and then back to a predicted UTC for Galileo system time. This is the way to come to the predicted UTC.

JACK TAYLOR (Boeing): Has Galileo settled on atomic frequency standards to be used on their spacecraft, and what is their redundancy? Has the project decided what kind of atomic frequency standards you are going to be using on board your satellites, and how many of them are there?

FURTHNER: I am not involved in the Galileo satellite designs, so I cannot answer this exactly. But I think it will be special rubidium clocks on it and maybe a passive/active H-maser will be on this, developed by either ESA or Temex in Switzerland.

WLODEK LEWANDOWSKI (Bureau International des Poids et Mesures): Could you comment again why Galileo single-channel common-view time transfer is significantly better than GPS single-channel common view?

FURTHNER: In this case, we have a better URE. In this case, we have a better URE of 1.3 meter from Galileo. If you compare it to a URE from GPS today, it is in the range of 5.1 meters.

BILL KLEPCZYNSKI (U.S. State Department): Just a small comment to make: you are comparing GPS today with the anticipated Galileo in 2010. I would think that it would only be fair to say what GPS, in 2010, will be providing too. So make that comparison.

FURTHNER: Correct. For this case, we have simulated GPS 2010 also. But we can also simulate this in the case that we do not exactly know the satellite constellation. We used the current existing satellite constellation, calculated the simulations with URE of 1.5 meters, which is published in the papers. Then with this compilation, we see that Galileo has an accuracy of 3.8 nanoseconds and GPS has 5.7 nanoseconds. This is what we expected.

The research people set it for the common view technology between PTB and DLR. It is based on the fact that we have real-time, real measurements of GPS. It is correct that GPS measurements may be better than expected as described in the official documents. Therefore, we also expect better values for Galileo in respect to what is presented in the official documents.