CLOCK STRATEGY EXPERIMENTATION WITH GIOVE CLOCKS

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INTRODUCTION

Estimation of Global Navigation Satellite Systems (GNSS) clocks phase is conventionally carried out by a geodetic network adjustment technique where orbits and all participant clocks are computed in a least square adjustment to a reference time scale and frame. For real time navigation satellite orbit and clock predicted values need to be provided to the user through the broadcast navigation message or other external means as ftp services, geostationary satellites or local networks. Whereas orbit prediction is quite stable across GNSS satellites and accurately predicted over one or several days, the clock phase among clock technologies is less homogeneous and difficult to be accurately predicted. The International GNSS Service (IGS) provides orbit and clock predictions with an associated accuracy information for its ultra rapid products in sp3-c format being the accuracy driven not by the clock itself but by the fitting quality and jumps in the frequency source.

The clock prediction strategy in terms of deterministic model and fitting intervals need to be tailored to the dissemination update rate and clock technology on board. The GALILEO testing satellites GIOVE-A and –B provide two different technologies of on board clock. Experimental results and hints from the GIOVE observations as well as theoretical analysis in terms of stochastic models give a deep insight on the on the clock predictability to be expected in particular with the GNSS on board clock.

CLOCK PREDICTION IN GNSS

Among actual GNSS the clock prediction error represents for real time navigation the main error contributor for dual frequency users and the second contributor for single frequency users behind the ionosphere, as acknowledged by the error budget of the actual leading system [1].

Since the early GNSS steps, clock error have steadily improved as soon as any new clock physical technologies have become available on board the navigation satellites. From early Cesium technologies (GLONASS and GPS), to the first free running Rubidium generation (GPS block IIA), to the second Rubidium generation or Time Keeping System technology (GPS block IIR) until the Passive Hydrogen Maser (Galileo), each technology has brought better clock prediction capabilities with the result of a mixture of clock technologies into space.

Clock prediction accuracy is inherently linked to age of data that is how old gets the prediction applied by the user with respect to the last data value used in the fitting [2], being the accuracy inversely proportional to the age. Data rate dissemination has improved within the broadcast message. Actual maximum latency following each system Interface Control Document (ICD) is at least 100 min for Galileo, twice a day for GLONASS and once a day for GPS. Higher update rate than the declared may be employed to adapt the prediction to the clock performance, as on GPS where up three-uploads-per-day instead of one may be applied in the case of less performing clocks [1].

Nowadays not only the broadcast navigation message is used for real or near real time navigation. A global GNSS user may employ full independent orbit and clocks information, provided by third entities as precise orbit determination centers [3], commercial services [4] or directly adding the station to the global network adjustment instead of using external orbit and clock information [5]. These entities provide independent messages by diverse communication channels and at different update rates, being the almost real time the final goal [6]. Actual limitation for IGS Ultra Rapid products is not the orbit but the clock prediction accuracy at 9 hours (3 latency plus 6 hours validity) and its robustness with occasional outliers [7]. On the other hand, previous IGS recommendations [8] called without implementation for the provision of accuracy values for the clock prediction which would allow the user to deal autonomously with different accuracies.

In parallel to the clock performance improvement through better clocks and refreshment rates the prediction robustness gain importance in order to meet International Civil Aviation Organization (ICAO) requirements that would satisfy en route, terminal, and precision approach operations [9]. In this line Satellite Based Augmentation Systems (SBAS) provide complementary information to the broadcast message in order to improve its robustness in terms of accuracy, reliability, continuity and availability. Galileo design and GPS evolution intends to provide their own integrity information [10].

The clock prediction strategy starts to acquire importance in order to improve the accuracy and robustness while dealing with a mixed configuration of clock families or even units with several efforts in this area [11]-[13] .Numerous publications are available on clock performance by navigation system and also for GIOVE clocks [14]-[17]. The purpose hereafter will be to provide an overview over actual GIOVE clock accuracy associated to each clock technology using a common approach and the feasibility to provide accuracy estimation to the prediction.

In the following sections the clock prediction strategy and associated stochastic model will be introduced. Afterwards a reference period will be selected over which different strategies will be applied. It will be demonstrated how the prediction strategy depends of the refreshment rate, main characteristics identified and some recommendations provided.

CLOCK PREDICTION STRATEGY

In order to achieve an accurate and robust clock prediction a dedicated clock prediction strategy is required in terms of:

1. Fitting model
2. Fitting intervals for the model
3. Outlier and operations rejection over the fitting interval.
4. Overall adequacy to the refreshment rate.

Outlier rejection deserves dedicated attention and it will be not addressed in this paper. A standard reference period without events is selected for analysis. As reference period one month from day 280 to 308 of the year 2009 has been selected. Main attention is given hereafter to the fitting model, data intervals for the model and the adequacy to the 100 minutes maximum validity time foreseen for the Galileo system.

Fitting Model

Orbit and clock phase estimations are performed using network adjustment techniques by each ground segment to a common reference frame and time scale. In order to generate a prediction for the user a linear or quadratic model (1) is fitted to the estimated clocks using least square adjustment techniques.

$$x(t) = \overbrace{\underbrace{\underbrace{a_0 + a_1 t}_{GLONASS} + a_2 t^2}_{GPS,Galileo} + a_3 \sin(2\pi\omega t + \varphi)}^{IGS} \qquad (1)$$

where:

a_0, a_1, a_2 , are the polynomial terms
a_{3}, φ , are the amplitude and initial phase of the harmonic

ω , frequency (inverse of the orbit period)
t , is the prediction time from t_0
t_0 , is the time for end of the fitting interval.

Each navigation system the model needs to be quantized and included in the allocated space into the broadcast navigation message. GLONASS only applies or allows for a linear prediction since uses only Cesium clocks. The quadratic term more adequate to describe clock frequency drift associated to Rubidium families is flexibly implemented by GPS and Galileo to be included or rejected depending of the clock drift behavior of each clock.

Presence of harmonics in the phase restitution of the satellite clock is a well known feature on satellite clocks [18]. A periodic function is recommended to be included by the IGS to the analysis centers [11] even if it is not clear from their analysis reports whether this recommendation is finally applied by each centre.

Once the model is estimated and the clock predicted the error x(t) associated to the model can be computed as the difference between the clock prediction and the posterior clock estimation. Assuming the atomic clock prediction mainly driven by white frequency modulation and flicker frequency noise the expected error may be computed following [2]:

$$\sigma_{x_p}(t) = \sqrt{\sigma_x{}^2 + \sigma_{a0}{}^2 + (\sigma_{a1}t)^2 + (\sigma_{a2}t^2)^2 + \left(\sigma_{yWF}(t)\cdot t\right)^2 + \frac{\sigma_{yFF}^2(t)\cdot t^2}{\ln 2}} \quad (2)$$

where

σ_x , is the clock phase estimation error computed or taken from the product accuracy.
σ_{a0}, σ_{a1}, σ_{a2}, are the uncertainty in parameters estimation obtained from covariance matrix of the adjustment.
$\sigma_y^2(\tau)$, is the Allan variance of the clock (White Frequency and Flicker Frequency) .
t , is the prediction time from the middle of the fitting interval.

Fitting Interval

Second important parameter in the prediction strategy is the fitting interval to compute the model and the outlier rejection on the fitting interval. A common period is normally used by fitting the clock model to the last 24 hours but a mixed approach can also be used by fitting different estimation intervals for each parameter e.g. a0 based in the last hour, a1 in 6 hours and a2 last 24 hours. Fig.1 illustrates the concept.

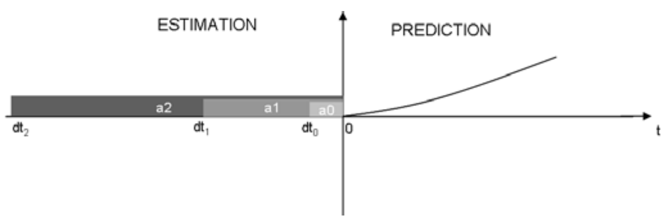


Fig. 1. Clock prediction model by fitting parameters a_0, a_1,a_2 to different dt_0,dt_1,dt_2 intervals

Any outlier, frequency step or maintenance over the fitting interval will impact the time prediction. Fitting interval should be preprocessed before final model adjustment.

EXPERIMENTATION

Currently broadcasted clock in GIOVE-A and –B navigation messages is computed using a common adjustment to the last 24 hours (dt0,dt1,dt2=24h) without any rejection strategy to the fitting data. Following this strategy the clock error is the main contributor in GIOVE broadcasted navigation message [19],[20]. Different strategies will be under test hereafter in order to improve the prediction accuracy and associated stochastic model.

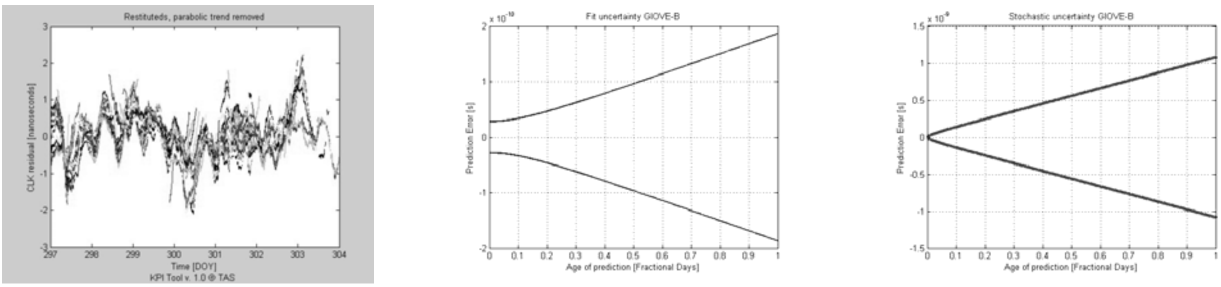
Strategy 0 – Different fitting intervals *dt*

First approach consists in use different fitting intervals to move t0 as close as possible to the prediction interval without losing accuracy in the parameters estimation. The following intervals have been selected (dt0=1h, dt1=6h, dt2=24h). In Fig. 2 the different contributors to the stochastic model have been quantified following eq.(2), where:

(a) The estimation error is computed by computing the 1-sigma distribution of the different estimation arcs. The estimation processing runs every hour computing clocks and orbit with the last 48 hours of data. As consequence 48 samples are available for each clock. An average value can be obtained as reference with 0.3 ns (1σ).

(b) The model for clock prediction is quadratic model where the parameters af2-af1-af0 are evaluated over the last 24-6-1 hours respectively. The theoretical model for the clock prediction error is the one reported in eq.(2). Such formula is correct under the hypothesis of independent estimates of fit coefficients. If the fit coefficients estimates are not independent some correlations terms appear and have to be taken into account in the uncertainty estimation. In order to eliminate such terms or to have at least negative correlations (which would not be a problem in the worst case analysis) baricentric coordinates have to be used in the polynomial fit estimate.

(c) The stochastic contribution on the uncertainty on clock prediction has been evaluated considering two types of noise: white frequency noise and flicker frequency noise. For GIOVE-B the values of such noises have been taken from the specs (ADEV at 1s 1E-12 for WFN and 1E-14 for FFN). For GIOVE-A the value of flicker freq noise has been taken from the specs (ADEV at 1s 3E-14) while for the white freq. noise the experimental value of 6E-12 has been considered, which is bigger than the value reported in the specs (5E-12). Combining the deterministic and the stochastic contributions, the 2-sigma total uncertainty is obtained:



(a) Estimation– 0.3 ns (b) Model error (c) Clock stochastic

Fig. 2 Different contributors to the clock prediction for GIOVE-B (PHM)

In Fig. 3 the different uncertainties are combined and compared to the clock prediction error as function of the prediction age. It can be noticed that the theoretical model seems to be not suitable for the experimental data, many prediction error curves are not contained in the 2-sigma theoretical uncertainty (red lines).

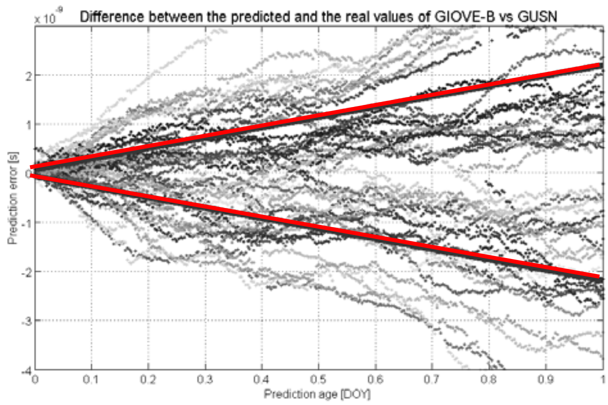


Fig. 3 GIOVE-B (PHM) clock prediction versus the stochastic model (2σ)

As observed on **Fig. 2**a a periodic function is visible on GIOVE-B clock. The higher error observed could be related to the periodic fluctuation which has not been taken into account in the model. This can be graphically verified in Fig. 4

where a linear fit to a simulated sinus signal of unit amplitude over the last 6 and 24 hours is computed. Neglecting the harmonic introduces a higher error in the model and the stochastic information derived in (b) is too optimistic.

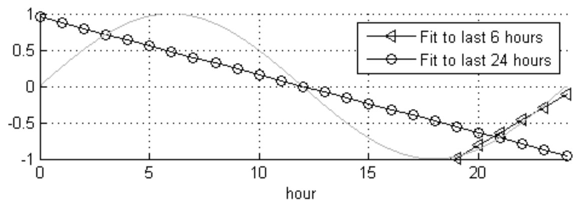


Fig. 4 Linear fit to a simulated sinus signal.

Strategy 1 - Inclusion of an additional harmonic term

Periodic phase variations associated to clock estimations are a common feature in GNSS satellites [17],[18]. From strategy-0 results it seems that the harmonic function can not be neglected without increasing the error. As consequence two additional parameters are included in the fitting adjustment in Eq.(3), where the harmonic period (1/ω) has been fixed to the orbit period.

$$x(t) = a_0 + a_1 t + a_2 t^2 + a_3 \sin(\omega t + a_4) \quad (3)$$

In Fig. 5 the clock prediction difference with respect to the reference is again plotted. It may be noticed as the 2σ uncertainty (red lines) contains the majority of the prediction error.

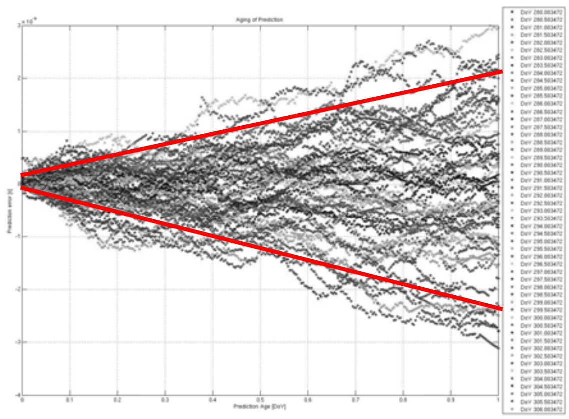


Fig. 5 Clock Prediction error with inclusion of the harmonic term versus the a-priori 2 sigma value

Strategy 2 - Inclusion of an additional harmonic term not transmitted to the user.

Following stochastic model analysis and results on strategy-0 the main error in the prediction was due to the increasing error in the model when this term is disregarded in the estimation. Once the harmonic has been included the fitting the model uncertainty contribution $(\sigma_{a0}, \sigma_{a1}, \sigma_{a2})$ should be improved. As the broadcasting of a five parameters clock model is not allowed by any GNSS navigation message at present [21]-[23], the next strategy will be to take advantage of this improvement by fitting a 5 parameters model while transmitting only the 3 quadratic parameters. As consequence the associated stochastic model defined in Eq. (2) will include a bias due to the harmonic contribution.

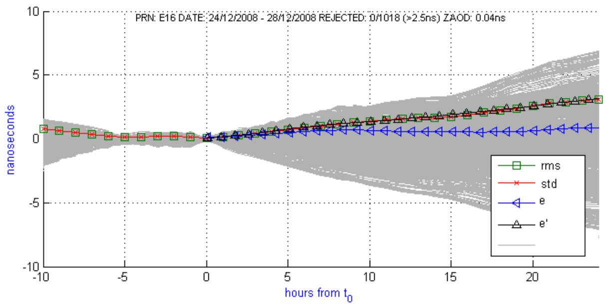
In order to remain within the 3 parameter model allowed by the broadcasted message, the new strategy-2 is tested by computing the prediction with the 5-parameter model and re-fitting of this 5 parameter prediction with only 3 parameters (to maintain a broadcast 3-parameter model) over the validity time of the clock model.

Strategy 3 - Different *dt* fitting intervals multiple of the orbit period

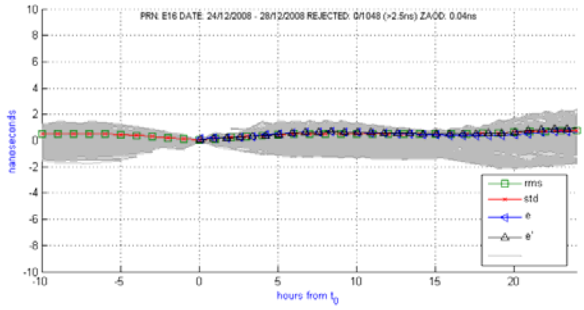
Little information exists about the harmonic source and characteristics. It is not clear whether the inclusion of the two additional terms (a3-a4) in the model will be robust or could introduce outliers increasing the maximum error. As consequence a simple approach is taken by selecting the fitting intervals (dt1, dt2) as multiple of the harmonic/orbit period.

The stochastic model defined in Eq. (2) needs to be reviewed. In strategy-0 the clock prediction has been computed at each sample interval (300 seconds). The clock model parameters computed are kept and the associated sigma over the fitting interval for this paramter computed ($\sigma'_{a0,a1,a2}$). This sigma will be used as a priori variance for the model error instead of the values derived from the least square adjustment ($\sigma_{a0,a1,a2}$). The a-priori error for the prediction following modified approach is noted as *e*'.

GIOVE-B orbit period is ~14 hours. In Fig. 6 the clock prediction is computed with dt1, dt2 multiple of the orbit period. The root mean square (rms) and the standard deviation (std) for the prediction error are computed at each prediction time. Both values present a good overlap indicating a zero mean unbiased distribution. The prediction error at one day is considerably reduced.



(a)



(b)

Fig. 6. Clock prediction for GIOVE-B (PHM) over 24 hours.
(a) fitting with dt0=1h, dt1= 06h, dt2= 24h
(b) fitting with dt0=1h, dt1= 14h, dt2= 28h (dt1,dt2 multiple of orbit period)

The theoretical stochastic model *e* seems to underestimate the real error diverging for prediction times over 6 hours, whereas the modified model *e*' follows with a better agreement the real error.

Summary

In all strategies is clearly observed how the accuracy is different at each prediction time. For short prediction times a short fitting interval could follow well the harmonic, as observed using the last 6 hours in the simulation performed in Fig. 4. As summary a final check is performed targeting the 100 min maximum validity envisaged in the Galileo navigation message with all the strategies under test and the one used for the current broadcasted values (BRD). Table 1 summarized the results for each prediction strategy from which several conclusions may be extracted.

Strategy				RAFS		PHM	
#	dt(0,1,2)	Estimation	BRD	rms	max	rms	max
BRD	(24,24,24)	a0-a2	a0-a2	7.31	12.62	0.38	1.46
0	(01,06,12)	a0-a2	a0-a2	0.97	2.74	0.37	1.43
1	(01,06,12)	a0-a4	a0'-a2'	0.70	2.13	0.33	1.73
2	(01,06,12)	a0-a4	a0-a4	0.70	2.13	0.33	1.73
3	(01,14,28)	a0-a2	a0-a2	1.48	4.48	0.27	1.34

Table 1 Clock prediction error at 100 min in [ns] with each strategy

Including the harmonic provides the best results for the RAFS. Strategy 1-2 provides the same results, as consequence it could be possible to improve the prediction error by increasing the model accuracy and remain within the actual two parameters in the navigation message. The broadcasting of the two additional parameters is not necessary at this prediction time.

For the PHM only small differences are observed by changing the strategy. The prediction at 100 min is limited by the 0.3 ns estimation accuracy. Including the additional coefficients associated to the harmonic the maximum error slightly increase for this data set.

CONCLUSIONS

GIOVE satellites broadcast currently a clock model in the navigation message which targets a maximum one day validity time. The associated accuracy is limited by the inadequacy of the model to the clock drift for the RAFS and to the presence of harmonics in the phase. The performance maybe increased by optimizing the fitting intervals and including an additional harmonic term in the clock model estimation. The associated stochastic model to the clock prediction is as well limited by the harmonic inclusion. A meaningful stochastic model associated to the prediction can be defined in case the harmonic is taken into account in the estimation.

Best clock prediction strategy is driven by the clock technology and validity time of the broadcasted clock model. Validity time is conditioned by the data retrieval, message computation and dissemination capabilities in the ground segment. For the 100 minutes validity time envisaged in Galileo, the RAFS benefits of the inclusion of the additional harmonic term without the need to transmit the harmonic terms to the user. In case of the PHM the prediction accuracy is limited by the estimation accuracy and no benefit is obtained from the inclusion of additional terms in the estimation, a simple approach to use fitting interval multiple of the orbit period provides slightly better results.

For this analysis the events have been avoided. In case robustness is targeted a more flexible strategy is required to deal with possible different clock technologies, unit behavior, system operations and frequency jumps.

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