GNSS clock prediction and integrity

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***Abstract*— Estimation of GNSS clocks phase is conventionally carried out by geodetic network adjustment techniques where orbits and all participant clocks are computed in a batch or Kalman Filter least square adjustment to a reference time scale and frame. For real time navigation this estimated clock has to be predicted and provided to the user through the broadcasted navigation message or other means as IGS ultra-rapid products.**

The present paper studies GNSS clocks prediction based on network estimations. Once the stochastic model is characterized for each GNSS clock technology detailed results are presented with dedicated attention to the clock prediction error, its gaussianity, overbounding possibilities and deterministic effects contribution, as frequency jumps, periodicities or group delay stability.

I. INTRODUCTION

Within the actual deployed GNSS the clock prediction error represents behind the ionosphere the second contributor to the error budget for single frequency users and the main contributor for double frequency users [1]. Additionally, integrity requirements gain importance in order to meet Civil Aviation requirements that would satisfy en route, terminal, and precision approach operations [2] making critical the integrity of the clock prediction..

This paper provides a detailed analysis of the clock prediction error for all GNSS available during 2007-2009. As GNSS will be considered any declared system with an open signal being transmitted during this period with a public Interface Control Document (ICD). As consequence, three systems can be considered GPS, GLONASS and GALILEO [3][4][5].

As GALILEO clocks will be considered the clocks on board the two experimental satellites, so called Galileo In Orbit Validation Elements (GIOVE). GIOVE satellites have an additional ICD [6] with an associated navigation message. However any assessment will be done with GALILEO Open Service ICD in view of the performance of the final GALILEO system.

Prediction times to be considered will be derived from the navigation message refreshment rate declared for each navigation system. Minimum refreshment rate following each ICD are at least, 100 min for Galileo, twice a day for GLONASS and once a day for GPS.

Higher update rate than the declared can be employed to adapt to the clock performance, as on GPS where up three-uploads-per-day instead of one can be used [1]. While navigation message refreshment rate in Galileo is sized to the clock prediction error associated to the RAFS (100 min.) the associated uplink ground infrastructure is sized to the Time To Alert (5.2 sec.) requirements for integrity. As consequence an almost continuous link exists between satellite and ground which could allow even faster refreshment rates of the few bits required by a linear clock model. Modernized GPS could broadcast in the future integrity information to the users [2] acquiring similar uplink capabilities.

Intention herein is not to analyze the Navigation Systems actual accuracy related to the clock but the potential performance achievable. Nevertheless, detailed analysis will be performed for highest and lowest declared update rate in order to provide an indicative accuracy figures i.e. 100 min and 24 hours prediction from estimation or Zero Age of Data.

In the following sections the clock prediction model and the overbounding concept will be introduced, a reference period selected, the error distribution in terms of Probability Density Functions (PDF) computed and overbounded. Finally, distribution and tails outside the core distribution will be analyzed, possible error sources studied and conclusions derived.

II. CLOCK PREDICTION

Orbit and clock phase estimations are performed using network adjustment techniques by each Ground Segment. 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. The model is quantized and included in the allocated space into the broadcasted navigation message.

$$x(t)=a_0+a_1(t-t_0)+ a_2(t-t_0)^2 \quad (1)$$

GLONASS only allows or requires a linear prediction whereas GPS and GALILEO implement an adaptive selection

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to include or reject the a2 term depending of the clock drift behavior.

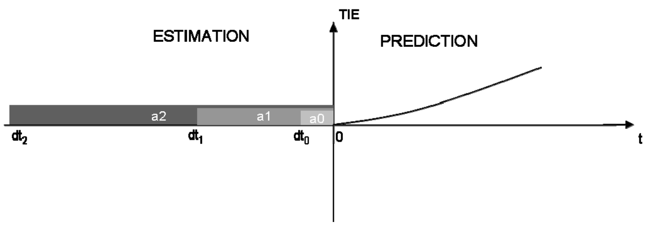

Figure 1. Clock prediction model fitting.

The Time Interval Error (TIE) associated to the clock model will be considered in this paper as the difference between the clock prediction and the posterior clock estimation. The fitting interval determines along with the clock stochastic characteristics the final TIE. As close as possible the fitting interval is to t_0 lower is the initial error but higher the medium and long term error. A flexible approach can be used by fitting different estimation intervals dt_0, dt_1 and dt_2 for each parameter. Fig.1 illustrate the concept.

To quantify the expected prediction error associated to an atomic clock its characterization in term of Allan Deviation $\sigma_y^2(\tau)$ can be used associated to the uncertainty in the parameters estimation [7].

$$rmsTIE(t) = \sqrt{{e_{a0}}^2 + (e_{a1}t)^2 + (e_{a2}t^2)^2 + (t \cdot \sigma_y(t))^2} \qquad (2)$$

Where

e_{a0},e_{a1},e_{a2}, ,are the uncertainty in parameters estimation

$\sigma_y^2(\tau)$,is the Allan variance of the clock

t ,is the prediction time from t_0

III. Data Set

In order to compare the satellite clocks a common reference period of analysis has to be selected for all GNSS. Galileo data are only available from the launch of the two experimental satellites and ground segment availability at the end of 2006. Therefore, the period from end 2006 till beginning 2009 has been selected to compare all clocks.

GPS and GIOVE clocks phase data are provided by GIOVE-Mission ground segment which realizes a combined estimation of both satellite orbits and clocks [8]. Products are obtained based in a limited number of 13 world wide sensor stations. This approach has been preferred to the use of IGS data for GPS since harmonizes both systems results and corresponds to an operational set-up.

GLONASS signals are not processed by GIOVE-Mission. IGS process dual frequency GLONASS signals jointly to GPS within the IGLOS pilot project [9]. Specific clock products in form of RINEX clock files are not generated, however final orbit solutions include the clock estimation simultaneously to the orbit estimations at 15 min. sample rate. These phase estimations have been used as baseline for GLONASS.

A. *Stability analysis*

Previous to computation of the TIE the dynamical Allan Variance is computed over the entire data set in order to gain visibility over the clock phase noise among the different GNSS. Harmonics presence in the phase restitution of the satellite clock is a well known figure on satellite clocks [10] . Allan Deviation is plotted for the 7 hours profile, which represents half of the orbit period for GIOVE satellites and will therefore maximize the visibility of any harmonic influence in the data. A reference line is drawn in red equivalent to $5 \cdot 10^{-12} \cdot \tau^{-1/2}$ with tau equal to 7 hours.

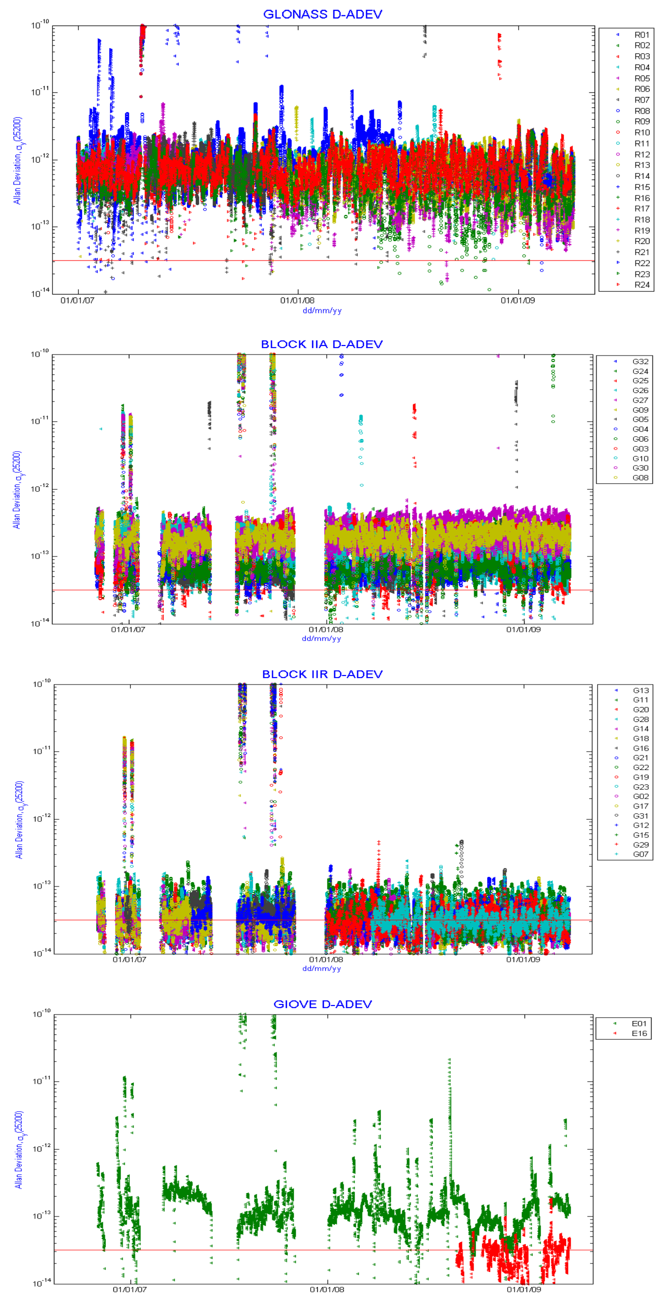

Figure 2. Dinamical Allan Deviation for each GNSS at 7 hours tau.

As can be observed on the Fig.2 the clock stability is different for each GNSS clock type, providing Block IIR and GIOVE clocks the best stability. On the end 2006 and middle 2007 a sudden increase of the instability is observed on all GPS and GIOVE clocks. Several data gaps are observed before 2008. GPS and GIOVE phase data source is GIOVE-Mission, therefore common effects are linked to the experimental GIOVE ground segment which become more consolidate from 2008. As consequence only phase estimation from 2008 onwards will be use to analyze the TIE over GPS and GIOVE satellites. Nevertheless the stability of this experimental set-up will still slightly affect the estimations, as observed on the common instabilities for E16 (PHM) and E01 (RAFS).

Several spikes are noticeable in Block IIA and in E01 clock. Frequency steps are a common feature in Rubidium technology and in GPS clocks [11]. These spikes are associated to frequency jumps on the clocks, as a reference an instantaneous frequency jump could originate an step of one third of its magnitude. Frequency steps are less obvious on Block IIR, for which the magnitude and occurrence has been reduced.

Clock technology is different among GNSS and inside each system. GLONASS is driven by Cesium clocks. GPS block IIA flies Cesium together with free running RAFS and block IIR uses steered RAFS (TKS). Galileo employs free running RAFS and PHM technologies.

GIOVE-A satellite (E01) can be as well differentiated between clock model, FM4 and FM5. While FM4 presents frequent steps FM5 does not show any significant step. FM4 has undergone significant mechanical stress which could explain this behavior, nevertheless several measures has been implemented in new Galileo clocks to decrease these feared events [12].

B. *PDF results*

To compute the TIE over the selected data set a sliding window approach is implemented. For each sample time (5 min. for GPS/GIOVE and 15 min for GLONASS) the clock model is computed, predicted and compared to the estimation. Finally for all clocks PDFs are computed. The selected strategy for generating the TIE is summarized in TABLE I. :

TABLE I. CLOCK PREDICTION STRATEGY

PARAMETER	GNSS	SELECTION
Data source	GPS/GIOVE GLONASS	GIOVE-Mission (clk) IGS (sp3)
Period	GPS/GIOVE GLONASS	2008/01/01- 2009/02/01 2007/01/01- 2009/02/01
τ, sampling	GPS/GIOVE GLONASS	5 min (clk) 15 min (sp3)
a_0, a_1, a_2, fitting	all	LSQ with dt0,dt1,dt2
a_2	G(IIR) E(PHM) rest	a_2 neglected = linear model a_2 included = quadratic model
dt_0, dt_1, dt_2	all	1 – 6 – 24 hours
t, prediction	GPS/GIOVE GLONASS	100 min, 24 hours 105 min, 24 hours

The PDF associated to each satellite at 100 minutes is showed in Fig.3 Values have been normalized in order to get a cumulative distribution function equal to one. Basic step to compute the PDF is 0.2 ns. GPS Block IIA and Block IIR are separated to differentiate among blocks. Important to remark the vertical scale is kept different in each plot for better visibility.

GLONASS shows a doubtful gaussianity. Distribution are in some cases biased, non symmetrical and with long tails. No clear different exist between older satellites and last launched.

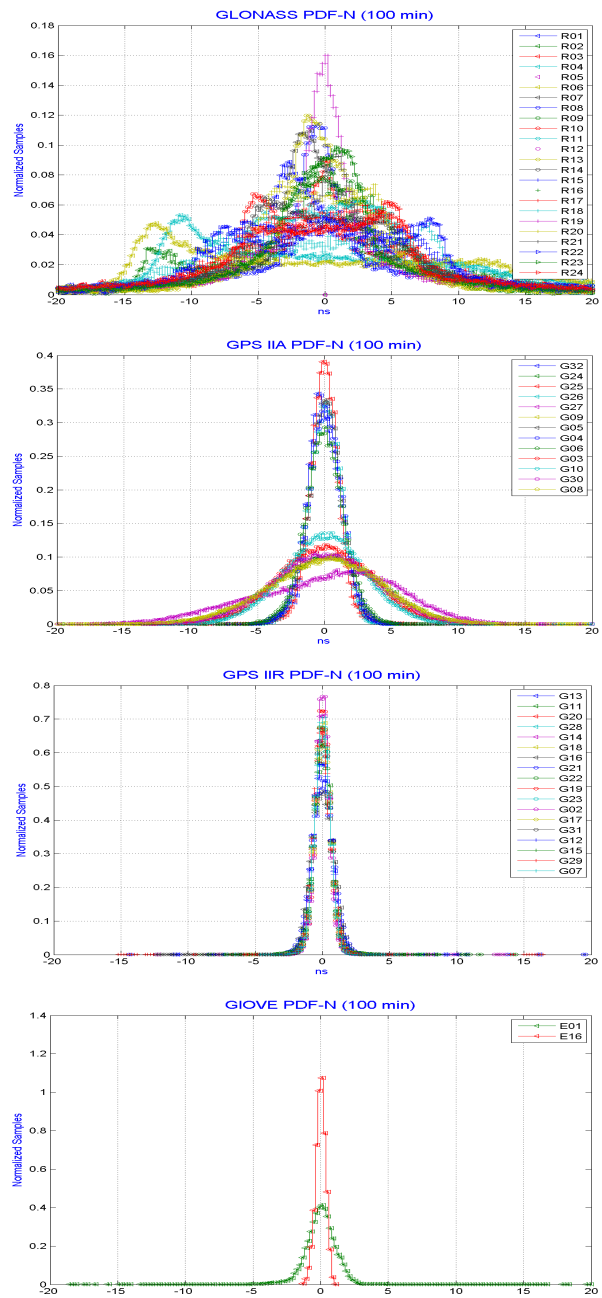

Figure 3. Probability Density Function associated to the TIE at 100 minutes for each GNSS from 2008 onwards.

GPS present a better gaussianity. Block-IIA shows the diverse performance of the different cesium and rubidium clock technologies on-board the satellites. Cesium clocks present a higher sigma than the RAFS. Distributions are well center in the zero being only G30 biased. Large tails are associated with all clocks. Block-IIR distributions are well center in the zero with lower tails and sigma. All GPS clocks are homogeneous by family, only the tails associated to the clock seem to be a characteristic of each specific model.

Galileo clocks on board GIOVE satellites are divided in RAFS (E01) and PHM (E16). Both distributions are symmetrical, centered in the zero. RAFS is characterized by longer tails, while as more important characteristic for the PHM its distribution have no tails.

C. *Clock Prediction Integrity*

Actual use of GNSS frequently lacks of a rigorous stochastic model associated to the deterministic model i.e. variance associated to the input observations is not provided or empirical fixed values are used. In order to provide an integrity service to the user an associated stochastic model has to be defined.

The stochastic model can be simplified if Gaussian zero mean distributions are associated to the observations and variance propagation laws are applied to the deterministic model. Once the variance linked to the navigation solution is estimated the user can compute integrity figures required to his needs, as integrity risk or protection levels.

Three major error sources can be defined linked to signal and navigation message generation, signal propagation from transmitting antenna to receiver antenna and signal processing by the user receiver. GNSS and SBAS requirements for integrity come from civil aviation where extremely stringent requirements for signal integrity, reliability, availability, and accuracy are defined [13]. Galileo and SBAS systems try to protect the users providing additional information about the first type, signal generation errors.

Main difficulties arise in overbounding the associated range errors with a zero mean Gaussian distribution since biases and large tails can be associated to the distribution. GALILEO and WAAS solution is to overbound the core of the distribution using a mathematical method [14] and assign probabilities to the tails of the distribution through analysis [15][16][17].

This approach obliges to limit the worst case behaviour of the clock errors outside the distribution and allocate a certain probability to any event. Assign these probabilities for a complete constellation with different clock technologies and clock behavior within families is not an easy task. Conservative approach should be used which can invalidate or hamper the complete integrity concept..

Fig.4 shows the final GNSS- PDF-Overbounded for all clock at the same scale in to provide a clear overview of the overall clock performance.

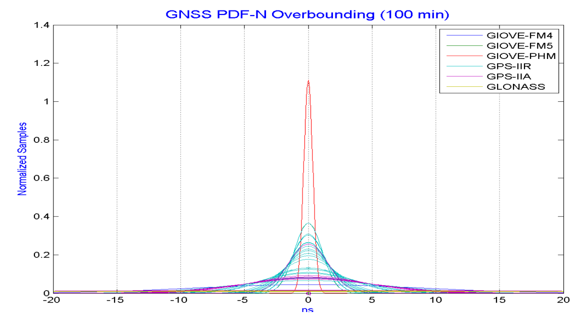

Figure 4. GNSS PDF overbound at 100 min

			100 min		24 h	
		PRN	1σ	$1\sigma_{over}$	1σ	$1\sigma_{over}$
		E01-FM5	0.7	1.1	14.3	18.2
GALILEO		E01-FM4	1.6	8.8	85.1	93.5
		E16	0.3	0.4	6.3	25.7
		G13	0.7	3.7	9.2	16.6
		G11	0.7	1.9	9.5	13.7
		G20	0.6	1.6	7.7	20.9
		G28	0.7	1.7	15.1	16.5
		G14	0.6	5.0	7.9	18.0
		G18	0.6	1.5	7.8	12.9
		G16	0.8	1.5	9.6	20.8
		G21	0.9	6.0	9.8	18.9
	IIR	G22	0.8	3.2	11.9	15.9
		G19	0.6	1.1	7.1	13.6
		G23	0.6	1.8	7.5	13.7
		G02	0.6	3.1	7.2	11.6
		G17	0.6	1.3	8.7	13.3
		G31	0.6	3.0	12.5	50.2
		G12	0.7	2.3	9.1	28.5
GPS		G15	0.7	2.0	8.8	26.4
		G29	0.7	3.8	10.1	44.0
		G07	0.6	1.3	8.0	13.0
		G32	1.3	1.6	18.9	22.4
		G24	4.1	5.1	57.8	60.9
		G25	7.3	26.2	150.5	326.3
		G26	8.8	27.0	16.5	30.3
		G27	11.8	26.8	79.9	95.9
		G09	4.1	4.9	56.4	58.2
	IIA	G05	6.5	25.9	44.8	261.4
		G04	19.2	31.5	24.3	235.2
		G06	21.7	32.5	24.7	236.4
		G03	3.5	4.3	47.4	56.7
		G10	3.9	26.5	224.5	350.3
		G30	3.9	4.7	49.1	55.5
		G08	4.2	5.4	53.1	56.6
		R01	28.8	39.5	316.4	406.2
		R02	27.0	37.4	398.6	425.3
		R03	52.1	40.6	412.7	435.3
		R04	25.4	35.9	320.2	408.1
		R06	25.1	34.5	323.1	404.6
		R07	29.1	36.7	288.7	402.4
		R08	36.0	43.4	389.1	458.6
		R09	18.1	32.9	226.4	402.2
		R10	23.0	35.8	286.5	405.3
		R11	20.2	36.2	251.9	411.0
GLONASS		R13	18.9	35.7	236.1	410.0
		R14	22.6	35.5	282.8	404.4
		R15	21.4	35.9	247.0	406.5
		R17	19.5	35.4	243.5	401.8
		R18	20.2	36.4	258.6	398.3
		R19	25.2	36.9	306.0	416.0
		R20	19.4	35.7	243.9	406.0
		R21	25.2	37.5	262.9	402.5
		R22	50.0	43.2	505.0	498.5
		R23	26.9	35.8	278.5	403.2
		R24	31.7	36.4	315.9	413.0

TABLE II. PDF OVERBOUNDING

TABLE II. shows TIE results in terms of one sigma at 100 min and 24 hours with ($1\sigma_{over}$) and without (1σ) overbounding. GIOVE RAFS clock has been separated into FM4 and FM5 and the first week of stabilization removed for FM5.

Two strategies can be used to compute the overbounding sigma ($1\sigma_{over}$). The complete or the core distribution can be overbounded by a zero mean Gaussian function. First option is chosen to take into account the distribution tails. Around 10^5 samples are used to compute the PDF and sigma values. Since the clock stochastic behavior is stable as demonstrated in Fig.2 and only affected by infrequent frequency steps, one sigma values (1σ) can be considered as the core distribution.

It has to be remarked as PHM on board E16 provides the best prediction in terms of lower sigma. At 100 min the prediction error is equivalent to the restitution error (0.3 ns). The no tails presence makes sigma and overbounded sigma almost equivalent at 100 min. For all the other clocks the inflation varies from 1 to 10.

D. *Error sources in clock prediction*

Error sources for clock prediction were defined in (2). Sigma values and PDF at a given prediction time characterize the error distribution, however no information is provided about the error components. Further analysis of the TIE is required.

In order to detail analyzed possible error sources the TIE as function of time is analyzed for GIOVE clocks. For the sake of visibility only December 2008 is analyzed representing the best performing period for E01-RAFS (FM5) in terms of Allan Deviation.

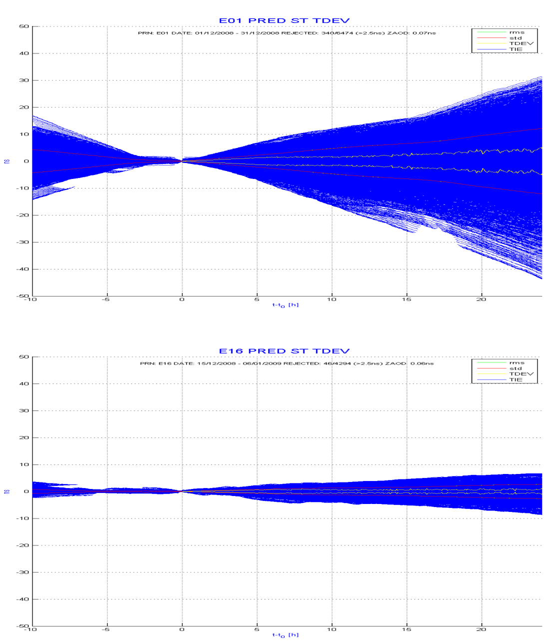

Figure 5. GIOVE clocks TIE for December 2008. RAFS (FM5) is located avobe and PHM below.

Fig.5 shows the TIE associated to GIOVE clocks for December 2008. Time Deviation (TDEV), Root Mean Square (RMS) and Standard Deviation (STD) values are computed for each prediction time. Plot has been extended to the previous 10 hours in order to provide visibility about the fitting interval.

RMS and STD functions fully overlap as expected indicating a zero mean unbiased distribution. TDEV diverges over 3 hours for the RAFS and 8 hours for the PHM into a lower value. Since the TDEV is only the last term in (2) the difference indicates e_{a0},e_{a1},e_{a2} increasing value over time and therefore the fitting inaccuracy to the clock model terms. This assumption is supported by the lower divergence for the PHM with respect to the RAFS, for which the a2 term is not estimated since a linear model is applied.

Further visibility can be gained plotting the TIE as a three dimensional (3D) function. Fig.6 shows the TIE for the PHM for 3 days over the selected period. The TIE-3D presents a clear harmonic contribution which increase with the prediction time.

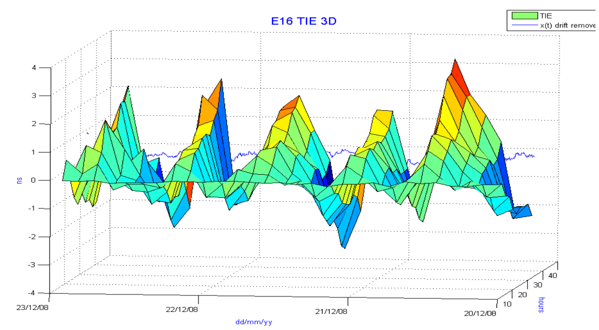

Figure 6. TIE-3D for GIOVE-B PHM clock and detrended estimated phase.

Blue line on the background has been introduced as reference. It represents E16 clock phase after a linear trend has been removed. The detrended phase shows a periodic fluctuation of 0.5 ns amplitude in the source data.

Actual GNSS clock models (1) do not take into account possible harmonic contributions to the phase. Additionally, LSQ adjustment to the phase data becomes not fully suitable in case of any harmonic presence.

Fitting error will be higher for a2 and it will depend of the fitting interval. In Fig. 5 the low dt0 (1h) keeps low the error at t0. The dt1 with a value (6h) different than a multiple of the harmonic period introduce an error in a1 term. The low dt2 (24h) introduces an error in the a2 term.

As final conclusion, TIE error is mainly driven at short term by the clock noise and at long term by the errors in the clock model estimation due to the harmonic presence. Periodic phase variations associated to clock and payload sensitivity to temperature are a common feature in GNSS satellites [10][19], therefore its presence should be taking into account when long predictions are required.

IV. CONCLUSIONS

Standard clock prediction models have been applied to all existing GNSS for two years of clock data. Results have been obtained in terms of Time Interval Error for different prediction times, error distribution derived and overbounded.

Main conclusions can be divided in three:

1) Prediction error at medium long term intervals are dominated by model errors due to periodicities in phase.

Periodic variations in phase are a common feature in GNSS clocks. When using standard LSQ fitting techniques these variations introduce errors in the clock model becoming the main error source from medium prediction times (e.g. 3h GIOVE-RAFS) depending of the harmonic amplitude. For long prediction time it will be adequate to use multiple of the orbit period for dt1 or introduce other adjustment algorithms.

2) Frequency steps in Rudium families hampers the provision of a meaninful integrity prediction.

GPS and Galileo distributions are unbiased, zero mean and symmetrical (good gaussianity), which is less obvious for GLONASS satellites. Complete distributions including the tails can be efficiently overbounded. Inflation factor between core sigma and overbounded sigma depends of the tail characteristics.

It seems possible to characterize core distributions for clock families by a single value (e.g. 0.8 ns for block IIR at 100 min). Once the distribution is overbounded and the tails taken into account discrimination among clocks is required. Since frequency steps dominating the tails are not a stationary process the significance of the overbounded sigma will depend of the sliding window used to compute the value and the rate of occurrence of the frequency steps.

On the other hand, WAAS and GALILEO try to overbound the core and characterize the tails. Assign probabilities for a complete constellation with different clock technologies, families and clock behavior within families oblige to use conservative approaches which can invalidate or bias the complete integrity concept.

3) PHM technology presents a promising behavior for navigation and integrity services.

PHM clock provide the best prediction figures and shows a tail free distribution simple to be overbounded and provide a robust integrity service. Nevertheless, only a few months of data are available for this technology which needs to be further validated in orbit.

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