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Space Clocks for Navigation Satellites

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Abstract–The estimation of prediction errors of the Galileo space clocks time is performed via the following steps:

a) the determination of errors induced by the geodetic measurement system noise in measuring and predicting the space clock time, based on measurements of GPS clocks produced by the extended GeTT experiment,

b) the elaboration of a theoretical model for estimating the clock prediction error due to the system noise,

c) the determination by laboratory measurements of the prediction errors of the Galileo clocks intrinsic to the clock characteristics,

d) the inclusion of the expected measurement system noise for predicting the Galileo clocks in space.

Finally a preliminary study, based on the results of the extended GeTT experiment, gives a rough estimate of the space clock time error bound due to the clock and the software outliers.

I. Introduction

In a satellite navigation system each satellite clock is affected by a time error increasing with the time elapsed from the last synchronization.

An important characteristics of the navigation system is the allowed time departure Δt (1 sigma) of the satellite clocks from the system reference clock for the navigation function. A clock model for each satellite clock is broadcasted from the satellites to the users for guaranteeing the specified navigation accuracy.

The ground control system corrects periodically the clock model parameters specific to each satellite clock for maintaining the time error within the specified limit.

The clock correction upload can be performed only at a maximum given rate determined essentially by the ground system infrastructure complexity. The ground system infrastructure therefore is imposing the maximum space clock free running time interval between two uploads which in turn determines the performance requirement of the clocks.

In Galileo the ground system is measuring continuously the space clocks with the purpose of uploading the proper clock corrections.

The clock corrections upload rate to be considered here is approximately 4 hrs.

The measurement by a ground system of clocks in space in quasi real time using a 1-way system as GPS or Galileo is not a trivial task.

Several sources of errors are presented:

a) errors in the measurements of pseudoranges with the ground receiver network which are assumed to be eliminated by the prescreening performed with the geodetic software, errors due to discontinuities in the clock output produced by the geodetic software at the boundaries of two data batches and orbit modeling errors. The last two errors are entering in the evaluation of the satellite clock time offsets from the reference clock. We simply referred to these errors as a "measurement system noise".

b) time prediction errors determined by the measurement system noise.

c) time prediction errors due to the intrinsic characteristics of the space clock.

Some of these aspects have been addressed partially from a theoretical and an experimental point of view in previous works [1,2]. However an experimental investigation of such errors in the case of quasi real time measurement of space clocks and for the relatively short averaging times of interest for Galileo has not been performed before and is presented here.

II. Estimating the the Galileo Space Clocks Performances

According to the present specification the Galileo space clocks predicted time error shall be less or equal to 1.5 ns (1 sigma) for a time interval between two uploads greater or equal to 4 hrs. This corresponds approximately to the performances of the best GPS space clocks presently operating.

In Galileo the measurement system selected for measuring the space clocks is based on the widely used geodetic technique [3].

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A variant of this technique is able to measure space clock time offsets in almost real time i.e at a rate of 5 minutes intervals [4].

According to the geodetic technique the clocks are measured over an interval Tm for evaluating the clock time offset, time drift and eventually the frequency drift from the reference clock of the system, using a linear or a quadratic model. The prediction of the time error over the following interval of duration Tp is performed using the same clock model.

For assessing the Galileo space clock performance it is necessary to determine, with the required accuracy, the sources of error in measuring and predicting space clocks:

a) the predicted time errors of some GPS clock are computed by comparing the predicted values with measured values as a function of Tm and Tp using the geodetic techniques implemented in the extended GeTT experiment.

b) the measurement system noise for measuring GPS clocks and the limitation imposed by the system noise in predicting GPS clocks are estimated.

c) a theory accounting for the error in clock prediction based on the measured system noise is also derived and successfully compared with the experiment.

d) the predicted time errors of the selected Galileo clocks, depending only on the clock characteristics, are computed by comparing the predicted values of the time errors with the values actually measured in the laboratory. The measurement noise is totally negligible in this case.

e) assuming that the measurement noise of the Galileo space clocks is the same as for the GPS space clocks, the Galileo space clock prediction error is computed taking into account also the contribution of the measurement system noise.

f) finally a preliminary analysis of possible outliers associated with the software or the GPS clocks is introduced for a preliminary estimation of an upper bound of the Signal In Space Accuracy (SISA).

III. The Extended GeTT Experiment

The extended Geodetic Time Transfer (GeTT) experiment, whose results are presented here, is the extension of a previous GeTT experiment, performed by Swiss Federal Office of Metrology and Accreditation (METAS) and Astronomical Institute, University of Berne (AIUB), focused on the comparison of the GeTT time transfer technique with the Two Ways Satellite Time Transfer (TWSTT) over intercontinental distance [5]. GeTT designates the Geodetic Time Transfer terminals developed by METAS. In the experiment two GeTT were deployed at PTB and USNO and connected under controlled conditions to the master clocks at those laboratories.

The scope of the extended GeTT experiment is the evaluation of the accuracy of the geodetic technique for ground and space clock measurements.

In the extended GeTT experiment, as in the previous experiment, a small subnet of 14 IGS stations located in the northern hemisphere is used for measuring the ground clocks. In addition, in the extended experiment, measurements of selected GPS space clocks using the Bernese software [3] are performed by METAS-AIUB. Simultaneously the same ground and space clocks are measured for the same epoch by GMV [4] with a geodetic technique having a quasi real time capability and based on a subnet of 24 IGS stations with a global coverage, independent from the Bernese subnet.

The clocks measured are: 4 GPS Rubidium clocks of block IIR (G-11, G-13, G-20, G-28) and 2 Cs clocks (G-02 and G-27). The ground clocks of high stability, common to the two networks, are the Masers PTBA (located at PTB Germany) and USNB (located at USNO USA). This last Maser is selected as the reference clock of the system.

For the 10 days duration of the experiment, the Bernese software clock data are available each 30s. The data are discontinuous, with exception of the ground Maser data, due to the limited number of ground stations associated with the GeTT subnet, allowing satellite observation only for about 50% of the time. In the case of the GMV software clock data are available each 300s and the data are continuous.

Concerning the measurements of the ground clocks the following results are obtained. a) The maximum difference between the Bernese GeTT technique and the TWSTT in measuring the time offset between the H Masers over 10 days is 1.5 ns. b) The differences between the Maser measurements using the Bernese technique and the GMV technique is 0.4ns RMS.

The accuracy of the geodetic technique for space clocks measurements can be estimated only by comparing the space clock results given by the two independent realizations of the geodetic techniques as implemented by the Bernese and the GMV groups. The RMS difference for the 6 space clocks measured using the two techniques is 1 ns, without rejecting any software outliers or clock outliers (see paragraph VIII).

In the following the clock data given by the GMV software are analyzed due to their continuity. The analysis of the data obtained with the Bernese software gives equivalent results, implying that the difficulties associated with measurement discontinuities are well compensated by the post processing and the use of precise GPS ephemerides in the Bernese software.

IV. Characterization of the System Noise for Measurements of GPS Clocks

The analysis of the space clock data provided by GMV is shown in Fig. 1.

The drift removed Allan deviation for the 2 best Rubidium clocks of Block II R (G13 and G20) is shown together with the data of 2 Cesium clocks. The Allan deviation with overlap corresponds to computing each new sample of the Allan variance by sliding the data trough the 5 minutes intervals. The results obtained using contiguous independent data for each new sample of the Allan variance, shown by the continuous lines, are practically the same. The removal of a relatively small uniform Rubidium frequency drift, of the order of 1×10^{-13}/day, is necessary for achieving the very high stability of the Rb clocks shown in Fig 1. On the contrary the drift removal does not improve the results for the Cesium clocks as expected. The results confirm that the Rubidium clocks are roughly a factor of 10 better than the GPS- Cs clocks for the averaging time of interest for Galileo. The main purpose of the Rb clocks measurements is the characterization of the measurement system noise which is possible only if the performances of these clocks are better than the measurement noise. This occurs to be the case for G-20 as shown below.

Fig. 2 reports the Allan deviation of the measurements of the Masers at PTBA v/s USNB using the continuous data available, in this case, from the Bernese software. There is no doubt that this curve represents the measurement system noise for measuring such ground clocks. In fact the intrinsic stability of the H Maser is definitely superior to the measured stability. The best-fit curve of the Maser Allan deviation v/s the averaging time has a slope of - 2/3. In Fig.2 also the Allan deviation of G-20 is reported. The best fit of this curve exhibits also a slope of - 2/3. The similarity of the two behaviors suggests that also in the case of the G-20 the Allan deviation is representing the measurement system noise.

This statement is supported by the following arguments:

a) the Rb G-20 exibits performances at the level of a ground H Maser. A quadraric fit of the time offset of G-20 over the 10 days of measurements gives residuals only a factor of 2 higher than the residuals of the PTBA Maser as

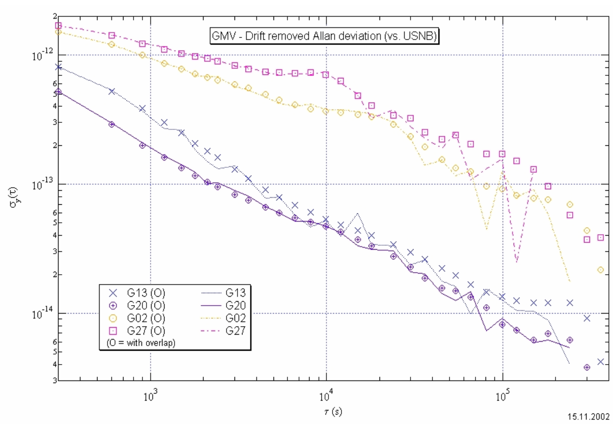

Fig. 1. Allan deviation of GPS S-clocks

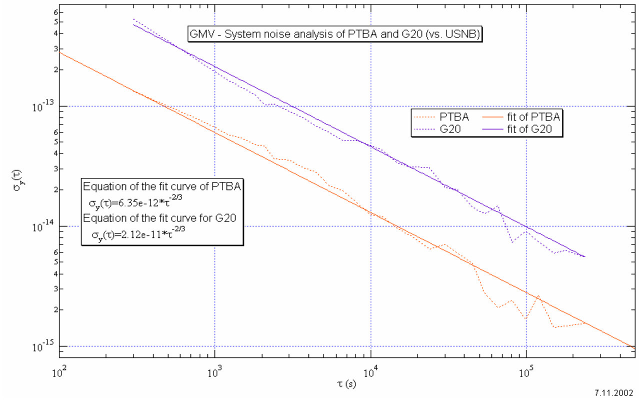

Fig.2. Measurement system noise

shown by the following results: the RMS value of the residuals of the Rb is 0.494ns, compared to the value of the PTBA Maser of 0.349ns; for the Rb the minimum and maximum time excursion of the residuals are respectively - 2.19ns and 1.22ns to be compared with the value of the PTBA Maser given respectively by - 0.92ns and 0.73ns.

b) theoretically the drift removed Rb clock stability is expected to have a behavior different from the one shown in Fig 2, i.e., corresponding to a white frequency noise.

c) a limited amount of clock-orbit correlation having a maximum of 1ns is known to be present in the actual realization of the GMV software. This time error is evolving with the period of the satellite orbit and introduces errors in the space clock measurements, which have a complex dependency on the exact epoch of the measurement and the satellite position. According to this interpretation it is not surprising that the ground clocks measurements, less sensitive to this effect, give a system noise which is reduced by a factor of 3 compared to the space clocks measurements as shown in Fig. 2. It is assumed that a reduction by a factor of 3 in the clock-orbit correlation could be gained in the future improved software to be implemented by GMV. This will improve the future space clock measurement system noise to the same value of the present ground clock measurement system noise.

V. Characterisation of the System Noise for Predictions of the GPS Clocks

It is possible to compare the clock time error predicted at the end of the time interval Tp, according to the geodetic technique described in section II, with the time error effectively measured at the time Tp. The RMS value of these differences is characterizing the clock prediction error at the time Tp. With a clock extraction each 300s it is possible to perform a new clock prediction every 300s. This is useful for improving the statistics for the larger values of Tm and Tp.

An example of clock prediction errors for the case of G-20 is given in Fig. 3 and Fig. 4. Note that, as demonstrated in the previous paragraph, errors in predicting this clock with a model taking into account its very uniform frequency drift, will be essentially determined by the system noise. The Figures show the results of the predicted time error as a function of Tp, for several measurement intervals Tm, using respectively a linear model or a quadratic model. As expected the quadratic model gives better results for the larger values of Tm and Tp being able to account for the frequency drift. However for the smaller value of Tp and Tm the linear model is superior. The results given in Fig. 3 and Fig. 4 are compliant with the ESA specification. The linear model is less dependent on possible fluctuations of the clock frequency drift, which are often encountered in space Rubidium clocks. The Rubidium clocks G-11 and G-13 are also compliant to the ESA spec with the linear model, while the Rubidium clock G-28 is out of specifications with any model.

The system noise for predicting the space clocks is determined alternatively from the prediction errors of G-20 using as input data the residuals of the parabolic fit of the G-20 over the 10 days. The results of the clock prediction errors using the residuals are shown in Fig. 5 with the label "experiment".

Fig. 5 shows also, with the label "theory", the results obtained from the theoretical model given below. The model is based uniquely on the knowledge of the drift removed Allan deviation of G-20 given in Fig. 2.

$$\sigma_{meas}(Tp,Tm)=\sqrt{\left(2.12\times10^{-11}\cdot Tm^{1/3}\right)^2+\left(2.12\times10^{-11}\cdot Tm^{-2/3}\cdot Tp\right)^2+\left(2.12\times10^{-11}\cdot Tp^{1/3}\right)^2} \quad (1)$$

The first term in the square root defines the error at Tp =0, i.e., the error accumulated by the clock during the measurement interval Tm and present at the start of the prediction interval Tp.

The second term, which is predominant, depends on the noise in determining the clock frequency offset (due to the clock frequency noise averaged over Tm). It affects the extrapolation of the clock time offset at the time Tp.

The third term is the random error accumulated by the clock during the prediction time interval Tp.

The model and the experiment are in very good agreement.

The system noise for predicting the ground clock time error is determined in a similar way. The input data are now the linear fit residuals of the time differences between the two ground Masers. The results are shown in Fig. 6. The theoretical model is based on the Allan deviation given in Fig. 2 for PTBA:

$$\sigma_{meas}(Tp,Tm)=\sqrt{\left(6.35\times10^{-12}\cdot Tm^{1/3}\right)^2+\left(6.35\times10^{-12}\cdot Tm^{-2/3}\cdot Tp\right)^2+\left(6.35\times10^{-12}\cdot Tp^{1/3}\right)^2} \quad (2)$$

VI. GALILEO SPACE CLOCKS STABILITY AND PREDICTED TIME ERRORS

The space clocks selected for the Galileo system are the space Rubidium Atomic Frequency Standard (S-RAFS) [6] and the Space Passive H Maser (S-PHM) [7]. More recently a laser Optically Pumped Ground Cesium beam clock (OP-G-Cs) has been considered for further investigation based on results obtained with industrial ground prototypes [8].

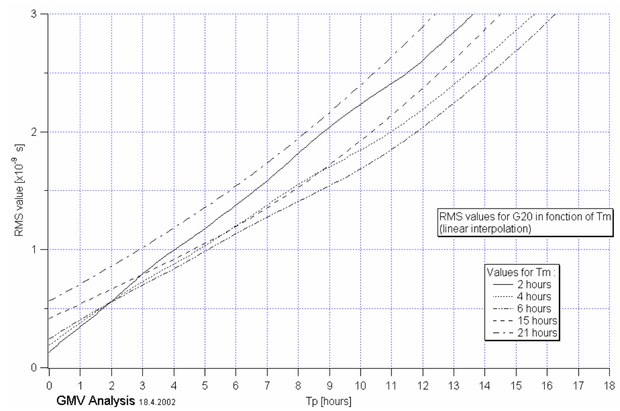

Fig. 3. Predicted time error for the Rb G- 20 (Linear model)

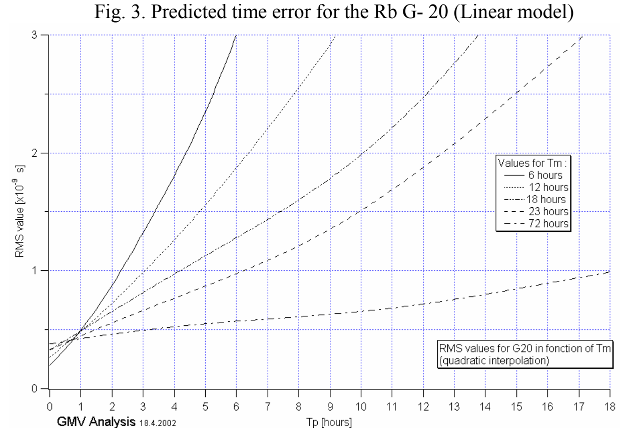

Fig. 4. Predicted time error for the Rb G- 20 (Quadratic model)

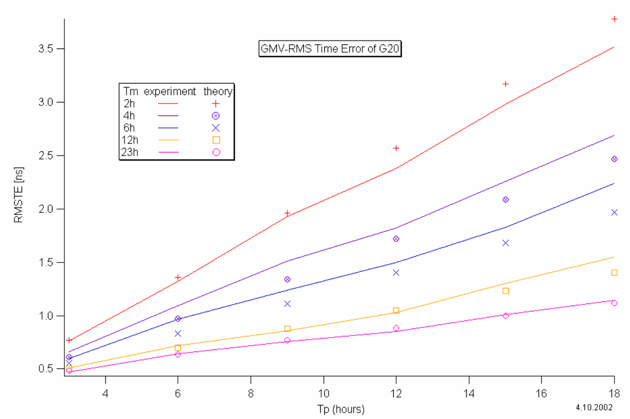

Fig. 5. System noise for space clocks prediction

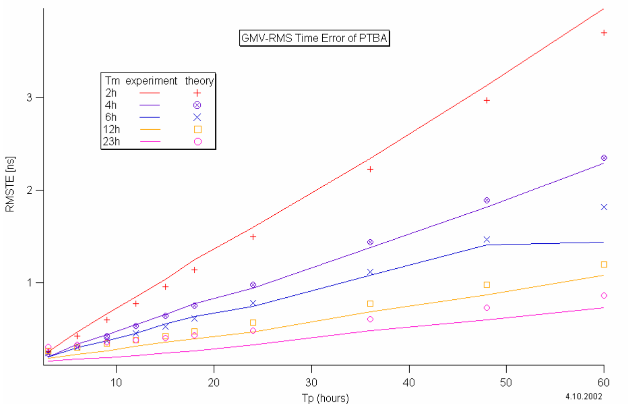

Fig. 6. System noise for ground clocks prediction

The laboratory measurements of these clocks have a totally negligible measurement noise and the pure clock behavior can be easily evaluated.

Fig. 7 shows the results of the Allan deviation of the above clocks. The drift removed S-RAFS stability is approximately the same as the stability of the OP-G-Cs, the latter having the advantage of no frequency drift. The S-PHM-EM (Engineering Model) stability is better than the Ground PHM (G-PHM) stability and is better than the S-RAFS stability by a factor varying roughly from 5 to 3 depending on the averaging time. The S-PHM and the G-PHM have a negligible frequency drift of the order of 1×10^{-15}/day. The predicted time error is shown in Fig. 8 and 9 corresponding respectively to prediction time intervals Tp up to 6 and 12 hrs using appropriate linear or quadratic models. The predicted time error of the S-RAFS is not improved for Tp up to 6 hrs using a quadratic model**.** It is roughly a factor of 3 higher than the S-PHM for Tp up to 6 hrs. For longer prediction time interval this factor increases further and reaches the value of 6 for Tp =12 hrs; the predicted error of the OP-G-Cs clocks lies in an intermediate region between the other two clocks. The pure clock time error bound relevant for the Signal in Space Accuracy is easily estimated by measuring the maximum predicted time error for each clock over the duration of the measurements. The results are given in Table I.

Also using this estimator the conclusion given above on the comparison of the clocks for the value of Tp of 6 hrs and 12 hrs are valid.

TABLE I
MAXIMUM PREDICTION TIME ERROR (ns)

	S-PHM EM	OP-G-Cs	RAFS
Tm=8h, Tp=6h	0.438	1.525	1.566
Tm=24h, Tp=12h	0.652	3.148	4.115

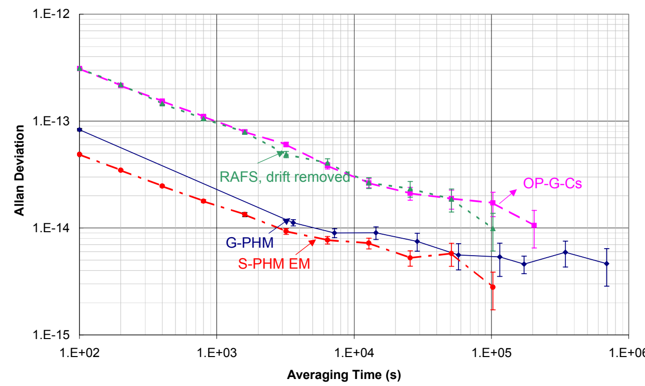

Fig. 7. Allan deviation of Galileo clocks

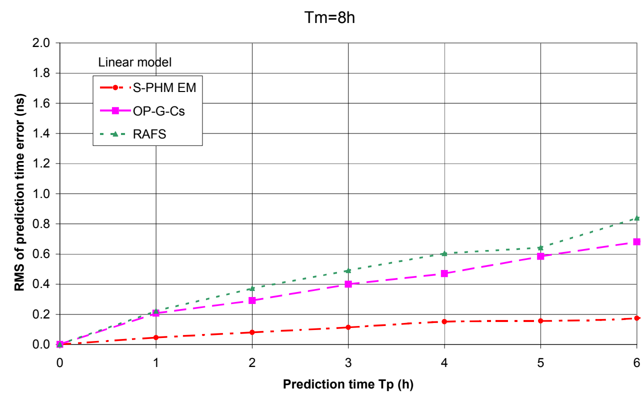

Fig. 8. Predicted time error of Galileo clocks (Tm=8h)

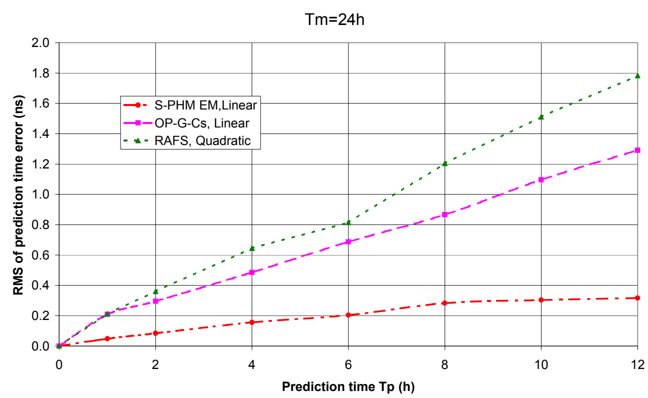

Fig. 9. Predicted time error of Galileo clocks (Tm=24h)

VII. GALILEO CLOCK TIME ERROR PREDICTION INCLUDING THE MEASUREMENT SYSTEM NOISE

Galileo clock prediction errors intrinsic to the clock and measurement system errors are in principle independent. The expected variance of the predicted time error of the space clocks in the operational Galileo system is the sum of the variance of the clock prediction and of the variance of the measurement system. This last variance is assumed to be the same as for the GPS space clocks measurements. Fig. 10 and

11 show the predicted clock time error including the present measurement system noise. The prediction of the S-PHM is degraded by more than a factor of 2. The S-RAFS predicted time error is whitin the 1.5ns ESA specifications up to 8 hrs, i.e., for a prediction interval which is a factor of 2 longer than specified. The S-PHM performances show a comfortable margin compared to the specifications.

Fig. 12 and 13 show the Galileo clock predicted time error obtainable with the improved space clock measurement system noise defined in section IV, i.e., resulting from the expected better handling of the clock-orbit crrelation. In this ideal situation the measurement system noise introduces negligible degradation also in predicting the S-PHM time.

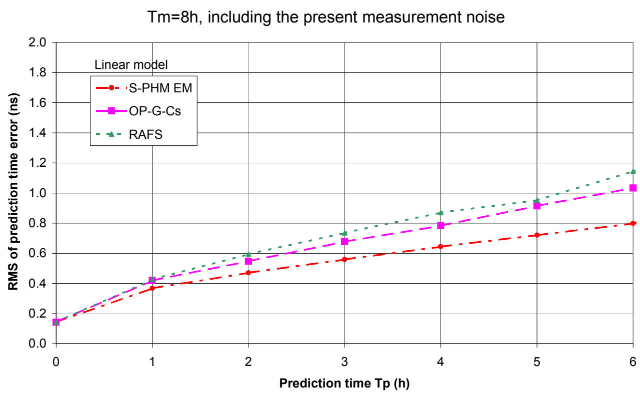

Fig. 10. Predicted time error of Galileo clocks including the present measurement system noise (Tm=8h)

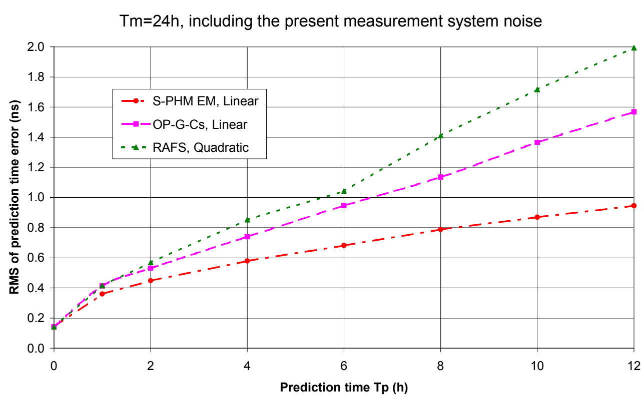

Fig. 11. Predicted time error of Galileo clocks including the measurement system noise (Tm=24h)

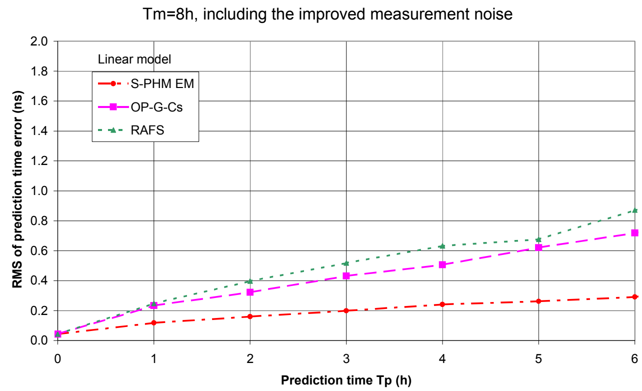

Fig. 12. Predicted time error of Galileo clocks including the improved measurement system noise (Tm=8h)

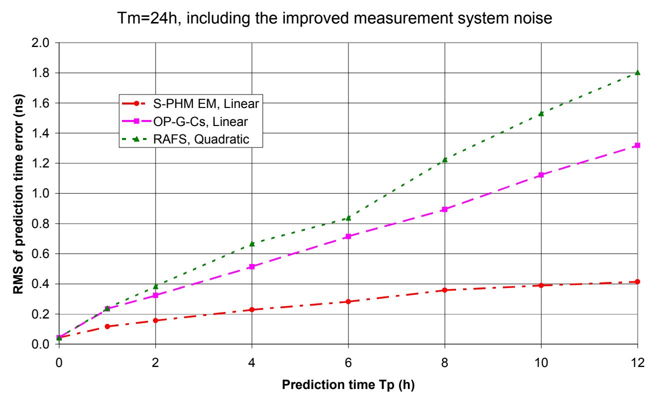

Fig. 13. Predicted time error of Galileo clocks including the improved measurement system noise (Tm=24h)

VIII. SIGNAL IN SPACE ACCURACY

The Signal In Space Accuracy (SISA) implies a definition of a bound of the space clock time error. A space clock time error greater than the bound determines a user range error exceeding a pre-set threshold generating an alarm in the system. The specification of this bound is presently in elaboration. The study of the clock outliers i.e. determined by real clock jumps or outliers related to discontinuities produced by the software is important in this context. By definition the clock outliers appear simultaneously in the Bernese and the GMV software. The software outliers appear only in one of the software.

In this work an outlier is defined as a clock residual of the quadratic fit over 10 days, differing by more than 5 sigma from the previous clock residual (i.e. measured 5 minutes earlier).

The distribution of differences between two successive 5 minutes measurements is first measured and fitted with a Gaussian function for obtaining the standard deviation. The 5 sigma values for the 4 GPS Rb clock measurements range from 0.65ns for G-20 to 0.91ns for G-11. With the limited statistics available for the 10 days of measurements we have detected only 5 GMV software outliers ranging between +1.9

ns and - 1ns. No clock outliers for G-20 were found. Approximately 30 clock outliers for all the other Rb clock (G-11, G-13, G-28) ranging between +2.1ns and - 1.5ns were detected.

These measurements suggest a preliminary value of the SISA bound for the software of about 2ns.

IX. CONCLUSION

The predicted time error of the Galileo space clocks for the navigation function is compliant with the present ESA specifications.

With the level of stability reached by the best GPS and Galileo clocks the measurement system noise of the quasi real time geodetic technique is contributing significantly to the space clock prediction error. Future improvements in the sofware could reduce the space clock measurement noise by a factor of 3 resulting in a negligible contribution to the prediction error for the best Galileo clock, presently the S-PHM.

A succefull theoretical model for estimating the effect of the measurement system noise in predicting the space clocks has been derived.

A preliminary determination of the bounds of the presently implemented geodetic software has been performed.

A systematic study of the software bounds and of the Galileo clock time error bounds remains to be performed in connection with the final ESA specifications of SISA.

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