Proc. EFTF 2005, Besançon, March 2005, pp. 438-441

Predictability of a Hydrogen Maser Time Scale

Laurent-Guy Bernier

METAS - Swiss Federal Office of Metrology and Accreditation
Lindenweg 50, CH-3003 Bern-Wabern, Switzerland
e-mail: laurent-guy.bernier@metas.ch fax: +41-31-3233573

Keywords: time scales, hydrogen maser, statistical prediction, optimal linear prediction

Abstract

The METAS Time & Frequency metrology laboratory has acquired a hydrogen maser in 2002. The maser was commissioned at the beginning of 2003. In June 2003 the maser started to contribute to the generation of the UTC(CH) and TA(CH) time scales. The Swiss time scales are currently generated from 3 cesium clocks and 1 hydrogen maser. The clock results are sent monthly to BIPM for contribution to the generation of TAI and UTC. The hydrogen maser is also used in combination with a DDS synthesizer to generate UTC(CH.R), a real-time realization of UTC(CH). The daily steering of UTC(CH.R) is based on a prediction of the hydrogen maser time scale over 1.5 d. Although the hydrogen maser does not have an Automatic Cavity Tuning (ACT) system, we have found that, despite the frequency drift, the time scale is extremely predictable.

1 Introduction

A constant drift is not a problem with respect to predictability. It is the presence of non-stationary discontinuities, such as spontaneous rate steps, that makes prediction difficult. In principle the time scale from an atomic clock affected by the classical set of noise processes (polynomial model) is a non-stationary process with Stationary Second Increment (SSI). SSI processes constitute the class of well behaved noise processes typical of atomic clocks for which the Allan deviation statistic is stationary. SSI processes are also tractable regarding prediction because it is possible to construct linear prediction operators for which the error on the prediction is stationary. Unfortunately atomic clocks are sometimes affected by spontaneous rate steps. It is necessary to detect, estimate and remove the rate steps from the time scale before attempting to apply a prediction algorithm because each step constitutes a discontinuity in the statistical properties which is disruptive to the statistical prediction algorithm. In the case of our hydrogen maser we have detected 4 spontaneous rate steps over a 590 d observation interval. The steps are of the order of 1 ns/d and their origin is unknown. One possible source could be the occasional sudden mechanical relaxation of the glass-ceramic microwave cavity. The present paper focuses on the outstanding frequency stability and predictability of our hydrogen maser.

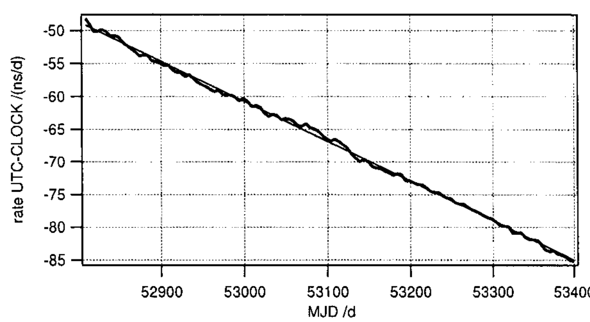

Figure 1: 5 d moving average rate of UTC-CLOCK for hydrogen maser ID 1405701.

2 Basic Time Scale Data

In the BIPM data base our hydrogen maser is known as clock ID 1405701. The basic time scale data is UTC-CLOCK /ns as published by BIPM. Changes in the calibration of the TAI common view GPS link have produced artificial time steps of -50 ns on MJD 53129 and +8 ns on MJD 53385. These steps were removed before analysis. The recorded span is from MJD 52809 to MJD 53399 (590 d) with a 5 d sampling interval. The 5 d moving average rate is shown on Figure 1. The average drift is -0.0607 ± 0.0002 (ns/d)/d. The observed stability includes both the intrinsic hydrogen maser frequency stability and the GPS remote comparison noise.

Proc. EFTF 2005, Besançon, March 2005, pp. 438-441

MJD	ns/d
52857	-0.85
53037	-0.92
53111	-0.85
53352	-0.38

Table 1: Rate steps removed from UTC-CLOCK process (clock ID 1405701).

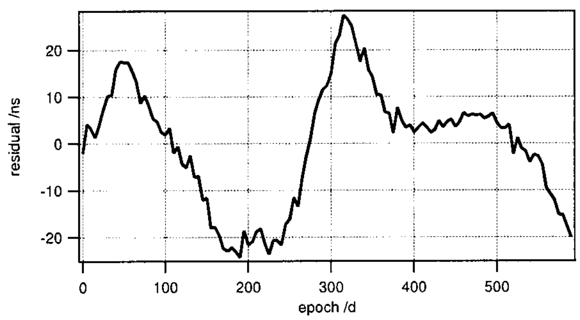

Figure 2: Drift removed residual of UTC-CLOCK before removal of accidental rate steps.

3 Rate Steps Removal

The approach to statistical prediction used in this paper follows a sequence of three operations: preprocessing, prediction and post-processing. The preprocessing consists into estimating and removing the spontaneous rate steps present in the original process. The post-processing consists into adding back the removed rate steps to transform the prediction of the pre-processed time scale into a prediction of the original time scale.

The accidental rate steps are detected and estimated by looking at the drift removed residual of the time scale process. A diverging residual is the sign of an undetected rate step. A rate step has two parameters: the epoch of occurrence and the rate offset. To estimate each rate step the pair of parameters is optimized to minimize the RMS drift removed residual.

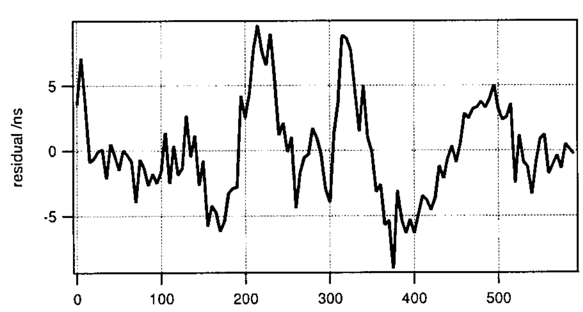

Figure 3: Drift removed residual of UTC-CLOCK after removal of accidental rate steps.

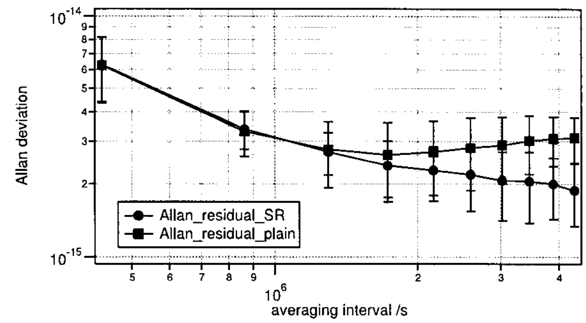

Figure 4: Allan deviation of drift removed residual of UTC-CLOCK with (Allan residual SR) and without (Allan residual plain) rate steps removal.

The four detected and removed rate steps are listed in Table 1. Figure 2 shows the drift removed residual before removal of the rates steps and Figure 3 shows the drift removed residual after removal of the rates steps. The drift removed residual before steps removal has a RMS deviation of 13 ns and is clearly not random. After steps removal the residual is more random and the RMS deviation goes down to 4 ns. Figure 4 shows the Allan deviation of the drift removed residual with and without steps removal. The Allan deviation after step removal is only 2×10^{-15} for an averaging time of 50 d.

The limited accuracy of the estimation of the rate steps does not affect the accuracy of the prediction. Each rate step removed from the original process to generate the residual is compensated by an identical rate step term used in the post-processing after the prediction. In this sense the separation of the original process into a rate steps part and a noise residual part is arbitrary. The requirement is that the residual process must be as close as possible to a SSI random process so that statistical prediction can be applied successfully.

4 Prediction Method

We use the DGSF-1 prediction algorithm for the prediction of the steps removed residual. The prediction algorithm is reported in details in [3]. The DGSF-1 prediction operator is a generalization of the simple second difference SF-1 prediction operator [2]

$$\hat{x}(t+\tau_1) = x(t) + \tau_1\, y(t,\tau_1), \qquad (1)$$

where the time process $x(t)$ is the integral of the instantaneous frequency process $y(t)$

$$x(t) = \int_{-\infty}^{t} y(u)du, \qquad (2)$$

and where $y(t,\tau)$ is the moving average of $y(t)$ over an averaging interval τ

$$y(t,\tau) = \frac{1}{\tau}\int_{t-\tau}^{t} y(u)du. \qquad (3)$$

In the SF-1 prediction the prediction $\hat{x}(t+\tau_1)$ is simply the present state $x(t)$ of the time scale process extrapolated into the future, assuming that the initial average rate $y(t,\tau_1)$ will not change during the prediction interval τ_1. In the SF-1 prediction the averaging interval of the rate is identical to the prediction interval and the RMS error on the prediction as a function of the prediction interval is given by the Allan deviation of the time scale process

$$\text{rms}\{\epsilon(t,\tau_1)\} = \sqrt{2}\tau_1\sigma_y(\tau_1). \qquad (4)$$

The DGSF-1 prediction operator, on the other hand, is a simple generalization of the SF-1 prediction

$$\hat{x}(t+\tau_1) = x(t) + \tau_1\, y(t,\tau_2) + \frac{1}{2}\,d\tau_1^2\left(1+\frac{\tau_2}{\tau_1}\right), \qquad (5)$$

where the averaging interval of the rate τ_2 is different from the prediction interval τ_1. This allows an optimization of the averaging interval τ_2 to minimize the RMS error on the prediction. d is a drift parameter that is also optimized in order to minimize the RMS prediction error. Its function is to compensate a deterministic drift in the time scale process.

5 Prediction Results

Figure 5 shows the sequence of all the individual prediction errors, for a prediction interval τ_1 of 50 d, that can be computed on the basis of the recorded steps removed residual. For a given prediction interval it is the RMS value of all past predictions that is minimized for the estimation of the optimum prediction parameters. In the present case the optimum prediction parameters are $d = -6 \times 10^{-3}$ (ns/d)/d and $\tau_2 = 115$ d. Using the optimal prediction parameters an RMS value of the prediction error of 5.5 ns is obtained.

6 Generation of UTC(CH.R)

UTC(CH.R) is a real-time realization of UTC(CH) which is performed by means of the daily steering of a DDS synthesizer which is driven by the free running hydrogen maser. The predictive steering method is reported in [4] and involves a prediction of the hydrogen maser time scale over a prediction interval of 1.5 d. Using the optimized DGSF-1 prediction algorithm, the RMS prediction error obtained over this prediction interval is 1 ns. A recording of UTC(CH.R)-UTC(CH)

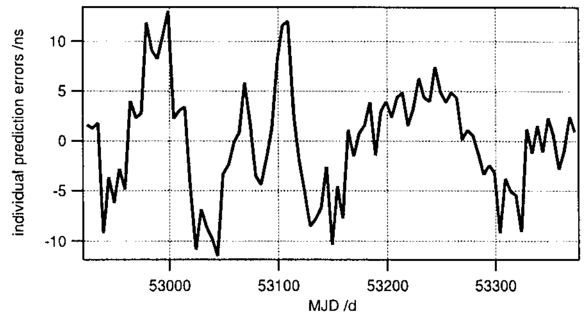

Figure 5: Individual prediction errors obtained by applying the optimized DGSF-1 prediction algorithm to the steps removed residual for a prediction interval of 50 d.

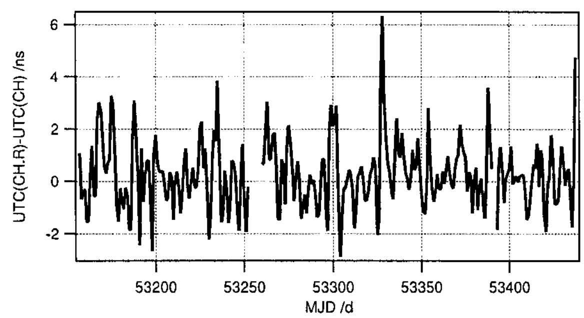

Figure 6: UTC(CH.R)-UTC(CH).

is shown on Figure 6. Thanks to the predictive steering control algorithm the experimental RMS deviation of UTC(CH.R)-UTC(CH) is only 1.3 ns. Simulations reported in [4] predicted a RMS value of 1.9 ns. Hence experimental performance is even better than expected. The visible spikes are due to the transient following each steering of UTC(CH). Just after a rate correction of UTC(CH) the prediction of the maser vs UTC(CH) is biased on the first day. The bias vanishes on the next day.

7 Conclusion

After estimation and removal of the spontaneous rate steps, the time scale of our hydrogen maser is predictable to 5.5 ns RMS over a prediction interval of 50 d. The drift and steps removed residual has an Allan deviation of 2×10^{-15} over a 50 d averaging interval. The observation that the hydrogen maser can have such an outstanding long-term stability without an ACT demonstrates once more that the design of an ACT system that actually removes the frequency drift of the hydrogen maser without degrading its intrinsic long-term frequency stability is a very demanding challenge. This paper shows that in some applications the drift can be compensated by software instead of relying on an ACT. Unfortunately the presence of spontaneous rate steps makes prediction more difficult. It would be very interesting to study the physical origin of the rate steps. The short-term predictability of the hydrogen maser time scale is also very good as illustrated by the performance of UTC(CH.R).

References

[1] L. G. Bernier, "Experimentation at METAS with a Simple Steering Algorithm based on Linear Prediction," in *Proc. IVth International Time Scale Algorithms Symposium*, BIPM, Sèvres, March 18-29, 2002.

[2] L. G. Bernier, "Use of the Allan Deviation and Linear Prediction for the Determination of the Uncertainty on Time Calibrations Against Predicted Time scales," in *IEEE Trans. on Instrum. and Meas.*, vol. 52, no. 2, April 2003, pp. 483-486.

[3] L. G. Bernier, "Application of the GSF-1 Algorithm to the Near-Optimal Time scale Prediction of the Hydrogen Maser," in *Proc. PTTI 2003*, San-Diego, December 2003, pp.221-236.

[4] L. G. Bernier, G. Dudle, "Practical Performance of the UTC(CH.R) Real Time Realization of UTC(CH) and Prospects for Improvement," in *Proc. EFTF 2004*, University of Surrey, Guilford, U.K., April 5-7 2004.