A NEW SYSTEM FOR THE GENERATION OF UTC(CH)

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Abstract

A new master clock definition of UTC(CH) was introduced in November 2007, replacing the original definition, a paper time scale. The new UTC(CH) was temporarily generated by prototype software. The final production software was commissioned in April 2011. The new system for the generation of UTC(CH) at METAS is known as ART (Autotime Real Time) after the original Autotime system it replaces, introduced in 1995.

HISTORY OF ART

The original *Autotime* system was developed at the Federal Office of Metrology during the period 1992-1994. *Autotime* was based on a paper clock definition of UTC(CH) and was running on a single computer under the HP-UX operating system. In 2002 we started experimenting with master clock steering algorithms and with time scale algorithm simulations **[1-6]**.

In 2006-2007 a prototype ART (*Autotime Real Time*) system was designed and tested **[6,7]**. The ART prototype was a hybrid combining the original *Autotime* system for the computation of the time scales with additional software and hardware for the generation and steering of a pair of redundant master clocks steered to the paper time scale. At the end of 2007 the official definition of UTC(CH) was changed from a paper time scale to a master clock hardware signal.

In 2011 the prototype ART system was replaced by the final production system. The ART system has three levels of redundancy that allow the maintenance of any part of the system without interruption of service. At the first level there are two master clocks and five atomic clocks in the ensemble which allows the replacement of any clock or master clock. At the second level there are two independent clock comparison systems which allow data substitution, in case of missing data, and continuous consistency checking and reporting of the clock data. At the third level there are two redundant control computers which perform independent calculations of the paper time scale, of the clock states and of the master clock steering parameters. Any system outputs inconsistency between the control computers is automatically detected and reported. The real time control software can be upgraded and the control computers can be rebooted or replaced without interruption of service.

This paper focuses on the ART software and system aspects. One of the most challenging requirements in the design of such a system is the fact that the time scale must be generated and delivered in real time, all the time, despite the hardware failures and the maintenance necessities that occur over the years.

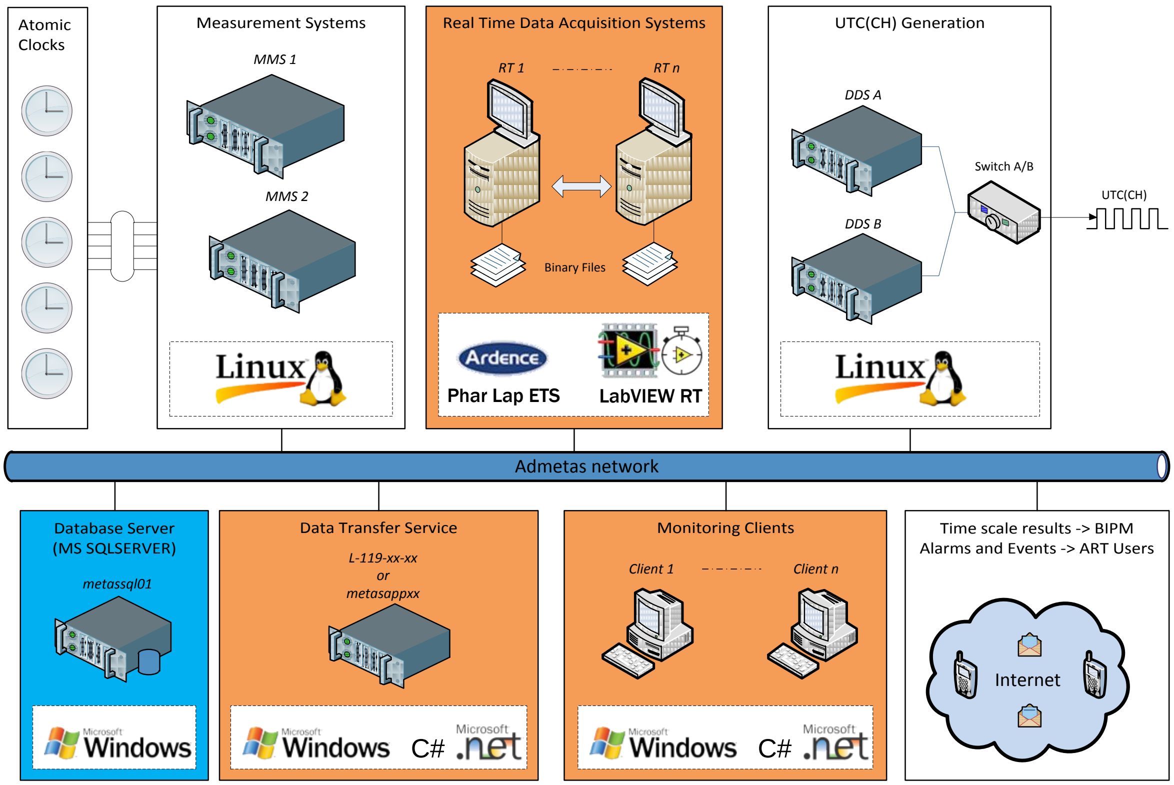

Figure 1. ART system architecture.

ART SYSTEM ARCHITECTURE

The ART system architecture is shown in Figure 1. It is a distributed system with the elements connected via the TCP network. The atomic clocks are measured by a set of two redundant 5-MHz Multi-channel phase Measurement System (MMS). The Master Clocks (MC) are generated by a set of two redundant 5-MHz Direct Digital Systems (DDS) that externally steer the frequency of a reference atomic clock. MMS-1 and DDS-A actually belong to the same electronics rack and are controlled by the same Linux controller, while MMS-2 and DDS-B are similarly controlled by a second Linux controller. On the other hand, the ART system is controlled by a set of RT systems, i.e. PC computer running the LabVIEW Real Time (RT) operating system. One RT system is the master, while a set of one or more backup RT systems can be configured. The other system elements are a Data Base (DB) Server and a few software services that can be hosted by any Windows computer.

ART SOFTWARE ARCHITECTURE

The ART LabVIEW RT software architecture is shown in Figure 2. Each RT system runs the same version of the software on a 4-core CPU. The master or backup status of each RT system is set by software configuration. As illustrated by Figure 2, LabVIEW RT allows the allocation of each process to any of the CPU cores. Time critical processes are given exclusive ownership of a core in order to guarantee perfect timing under any circumstances. On the other hand, several non time critical processes can share the same core without problem.

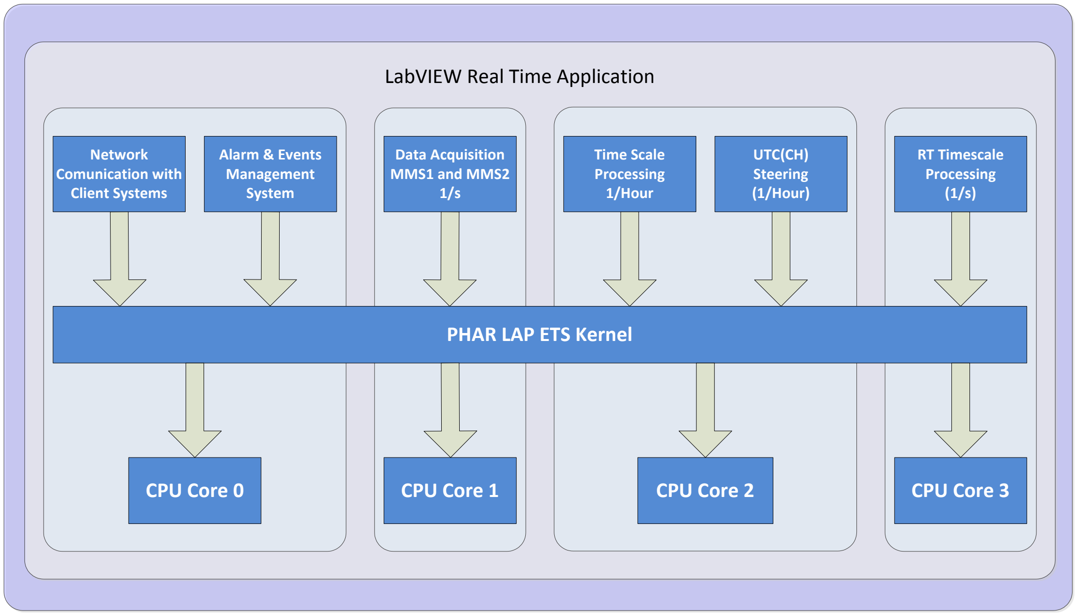

Figure 1. ART real time software architecture.

The system architecture is very flexible. Only the master RT system actually controls the steering of the MC's and uploads the time scale results to the Data Base. The single or multiple backup RT systems, on the other hand, compute all the system outputs but do not actually control anything. Hence it is possible to simultaneously run the ART production system, which controls the MC's and generate UTC(CH), and an experimental ART system which can be used to test or validate alternate algorithms and software. The production and experimental systems can share the same clock data in real time.
Every 10 minutes all the system outputs from the master and backup RT systems are compared. Any inconsistency generates an alarm. Hence, when there is no current alarm the operator can be confident that the backup system is in perfect agreement with the master system. In case of a failure of the master RT system, one of the backup systems can be given the master status and take over the steering of the MC's and the upload of the system outputs to the DB.

GENERATION OF THE PAPER TIME SCALES AND OF UTC(CH)

The realisation of UTC(CH) is chosen from one of two redundant master clocks: MCA and MCB. Each master clock is actually the output from a DDS which steers in frequency the 5-MHz signal from a reference atomic clock selected in the ensemble. An Auto-sense Fault Switch (AFS) is used to select which master clock defines UTC(CH). Four cesium clocks and one hydrogen maser are used for the time scale generation. Two paper time scales are computed daily on the basis of the ensemble of free running atomic clocks using the AT1 NIST algorithm **[8]**. TA(CH.P) is a free running time scale, while UTC(CH.P) is steered monthly to track UTC **[8]**. Besides, an auxiliary time scale UTC(CH.H) is computed every hour. The auxiliary time scale uses the last computed daily state of UTC(CH.P) as an initial condition and is used to extrapolate the daily paper time scale up to the current epoch. The MC's are steered every hour to track the auxiliary time scale **[8]**. Since the sampling interval is one hour, it is possible to steer a MC with a control loop time constant time as short as one hour. On the other hand there is no upper limit to the control loop time constant which can be optimized for the best short-term stability **[8,10]** for each MC.

CLOCK HEALTH CRITERION

The auxiliary time scale UTC(CH.H) is computed every hour while the main time scale UTC(CH.P) is computed every day at UTC 00:00:00. For any clock in the ensemble we define the relative rate error ρ in two varieties:

$$\rho_1(t) = \frac{y(t,\tau_0) - y(t-\tau_0,\tau_0)}{\sqrt{2} \times \sigma_y(\tau_0)} \quad (1)$$

$$\rho_2(t) = \frac{y(t,\tau_0) - y(t,n\tau_0)}{\sqrt{2} \times \sigma_y(\tau_0)} \quad (2)$$

where $y(t,\tau_0)$ is the current relative frequency of the clock over the last time scale computation periodτ_0, i.e. one hour or one day.

$$y(t,\tau) = \frac{1}{\tau}\int_{t-\tau}^{t} y(t)dt \quad (3)$$

Here $y(t,n\tau_0)$ is the average relative frequency of the clock, averaged over n periods, for example 30 days. $\sigma_y(\tau_0)$ is the Allan deviation of the clock over the computation interval. As a matter of fact ρ_1 is the frequency deviation from a period to the next while ρ_2 is the frequency deviation from the average. Since the Allan deviation characterizes the RMS relative frequency change from period to period, that means that for any healthy clock, the standard deviation of ρ_1 is equal to one. Therefore the standard deviation of $\rho_2 \cong \rho_1$ should also be approximately one for a healthy clock.

$$\langle\rho_2(t)\rangle_{RMS} \approx \langle\rho_1(t)\rangle_{RMS} = \frac{\langle y(t,\tau_0) - y(t-\tau_0,\tau_0)\rangle_{RMS}}{\sqrt{2} \times \sigma_y(\tau_0)} = \frac{\sqrt{2} \times \sigma_y(\tau_0)}{\sqrt{2} \times \sigma_y(\tau_0)} = 1 \quad (4)$$

At each computation of the paper time scales, i.e. every hour, the ART system computes the relative rate error ρ_2 for each clock and if the value is higher than a programmable threshold value, usually 5, the clock is considered as unhealthy and removed from the time scales.

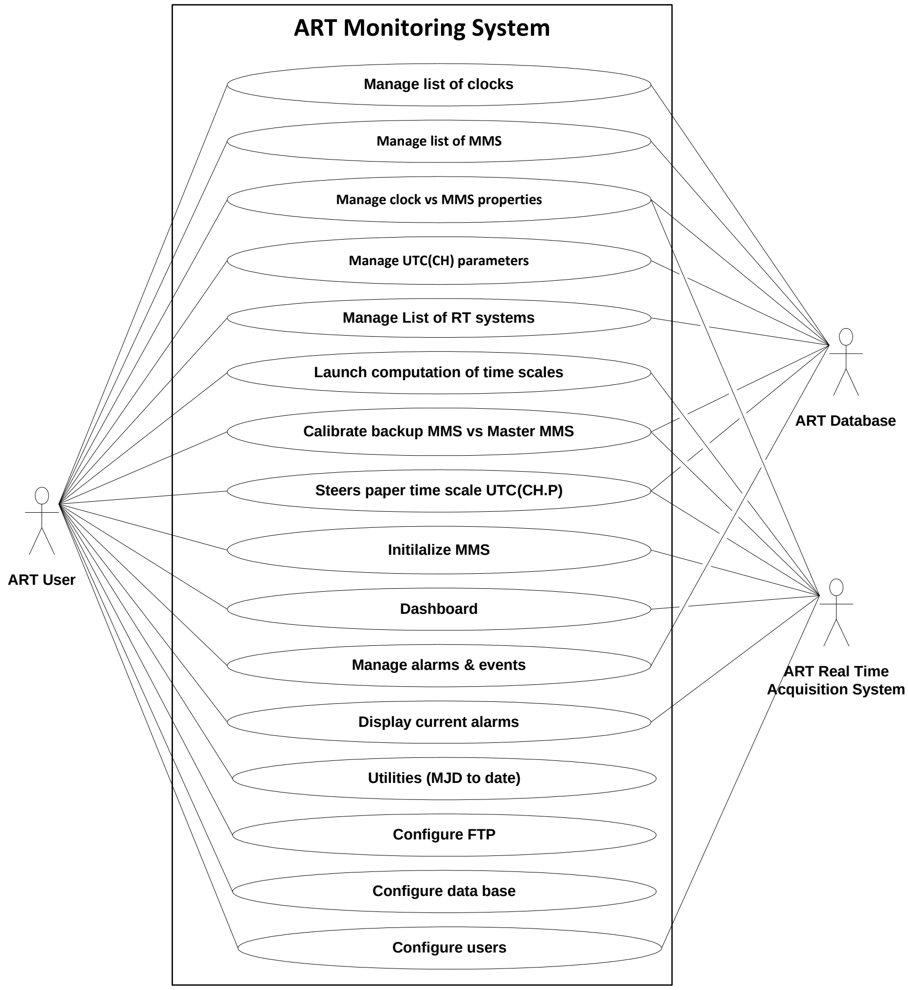

Figure 3. UML (Unified Modelling Language) diagram of ART monitoring system.

ACQUISITION OF CLOCK DATA

The clock difference measurements are based on a pair of redundant 5 MHz MMS's. The time deviation measured between two channels is 0.15 ps over 1 s integration interval (white noise) and the flicker noise floor is 0.02 ps over > 100 s integration interval **[7]**.

The LabVIEW RT (Real Time) software that runs on the redundant RT systems acquires the clock time differences from the two MMS's. Actually the Linux controller in each MMS is able to manage multiple telnet sessions via the network. Hence the two redundant RT systems can listen simultaneously to the pair of MMS's.

In practice, the last reboot epoch is different for each MMS and the delays in the coaxial cables that connect the atomic clocks to MMS-1 and MMS-2 are also different. As a consequence the raw data from MMS-1 and MMS-2 are not the same. However, an automated software calibration process allows the computation of a set of calibration constants that makes the computed clock time differences identical between the master MMS and the backup MMS. If for some reason, possibly network problems, some clock data from the master MMS are missing, the corresponding clock data from the backup MMS is substituted.

In the worst case, when no data are available from any of the MMS's at the exact epoch of the beginning of the hour, i.e. when the auxiliary and/or main time scales are computed, then the last available clock difference measurements are extrapolated using the estimated average frequency of each clock. Hence the computation of the time scale is always possible, even when the relevant measurements are missing. Moreover this scheme allows the modification of the cabling of the atomic clocks without interrupting data acquisition. Suppose that one wants to modify the cabling between the clocks and MMS-2. Using the user interface MMS-1 is set to be the master, then the cabling of MMS-2 is modified, and finally, with a simple command, the backup MMS-2 is automatically calibrated against the master MMS-1.

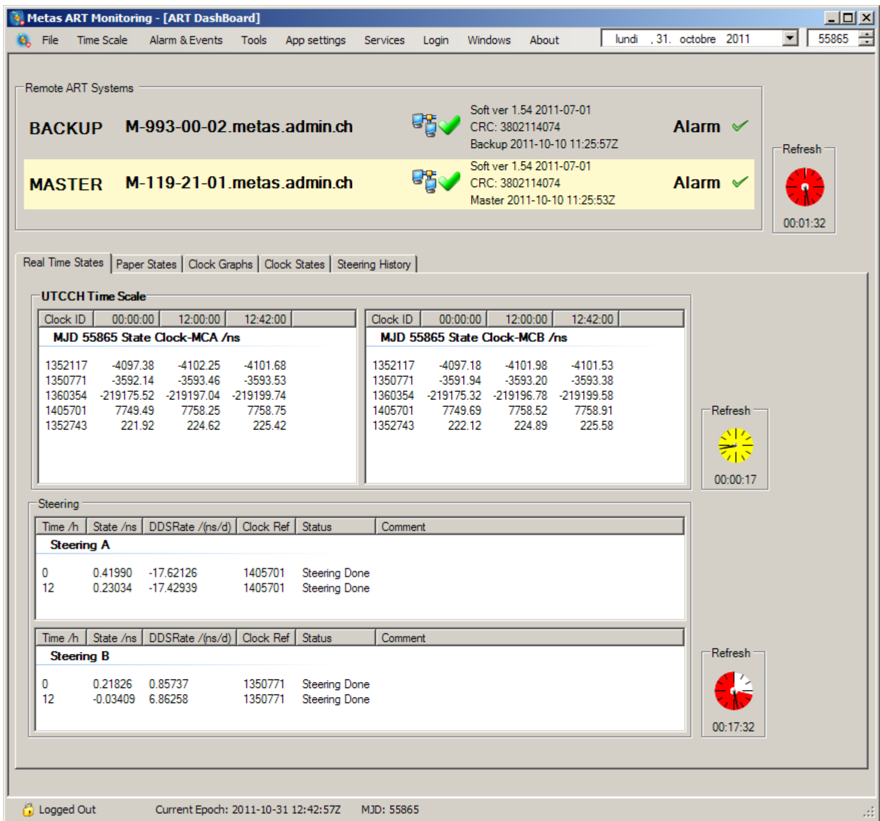

Figure 4. Example of user interface dashboard.

DATA TRANSFER SERVICE

As illustrated in Figure 1, a Windows service runs continuously and periodically checks what data records from the master RT system are already stored in the DB server. New data are automatically stored in the DB. At any time, all the data generated during the last 3 months are stored locally in each RT system. Hence if the data transfer service is temporarily stopped, or if the DB server is temporarily unavailable, no data are lost. In case of a failure of the master RT system, the missing data can be recovered from the backup RT system.

USER INTERFACE SOFTWARE

The user interface software runs independently on any computer. It communicates both with the data base server and with the RT systems. When the user wants to change the system configuration, for example introduce or remove a clock from the time scales, or apply an automated procedure, for example steering the paper time scale or calibrating the backup MMS vs the master MMS, the new configuration or procedure is first created in the data base. Then, in a second step, the new configuration or procedure is sent to the RT systems which send in return an acknowledgement message. The user can therefore determine at any time if/when a procedure or configuration was created in the DB and if/when a procedure or configuration was downloaded and applied by a given RT system. Figure 3 lists the main functionalities of the user interface. The user interface application interacts with the user, with the DB server and with the RT systems master and backups.

Figure 4 gives an example of the ART user interface dashboard. As illustrated, the network identity of the master and backup RT systems is clearly indicated as well as the version of the real time software and the epoch of the last reboot. The state of each clock vs MCA and MCB is displayed for epochs midnight, the last integer hour and the last integer minute. The state and rate correction of MCA and MCB vs the paper time scale is displayed for the epoch of the last steering, i.e. the beginning of the current hour.

TYPICAL SYSTEM OUTPUTS

Figures 5 to 9 show typical recordings of the 5 clocks that participate to the generation of UTC(CH) and TA(CH). In these examples, UTC(CH) is defined as MCA, i.e. the hydrogen maser steered to the paper time scale UTC(CH.P). TA(CH) is the same as UTC(CH.P) but free running, i.e. not steered. The states of TA(CH)-UTC(CH) are paper states reported versus MCA like any other clock. The daily clock states reported in the graphs are computed versus UTC. The daily values are based on an interpolation of the 5 day interval UTC-UTC(CH) values published in Circular T by the BIPM.

In Figure 5, a constant time offset and a constant frequency offset was added to TA(CH) so that it matches UTC(CH) between MJD 55630 and MJD 55657. This makes visible the steering of UTC(CH.P) applied on MJD 55657. On MJD 55700 the relative rate error of clock 1360413 reached a value of 4 (beyond 5 the clock is automatically removed from the time scales). After verification it was determined that the cesium tube of this clock was in end-of-life conditions: the electron multiplier voltage had reached the maximum value and the electronics gain was increasing. It was decided to plan the removal of the clock from the time scales. The clock was actually removed from the time scales on MJD 55742, i.e. at the end of the recording of Figure 6.

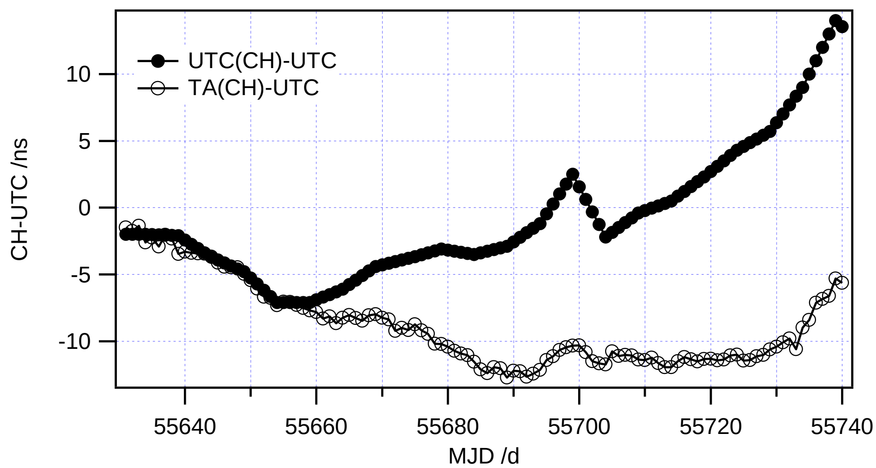

Figure 5. Recording of UTC(CH)-UTC and TA(CH)-UTC.

In Figure 5 one can also see that another incident occurred on MJD 55700. There was a problem with the steering of MCA which caused a step of UTC(CH). However the paper time scale was not affected and since the MC's are steered to track the paper time scale on the long-term, a temporary problem with the steering of a MC does not have any consequence on the subsequent behaviour of UTC(CH).

Figure 7 shows the recording of the two high performance cesium clocks. One can see that one of the clocks is more stable than the other.

Figure 8 shows the recording of the hydrogen maser CLK 1405701 versus UTC. One can see that the drift of the maser, about 1×10^{-16} per day, is very stable. Figure 9 shows the residual after removal of the drift. The time deviation from a parabola, i.e. pure drift model, is only $\pm$1.5 ns over the 100 day recording interval.

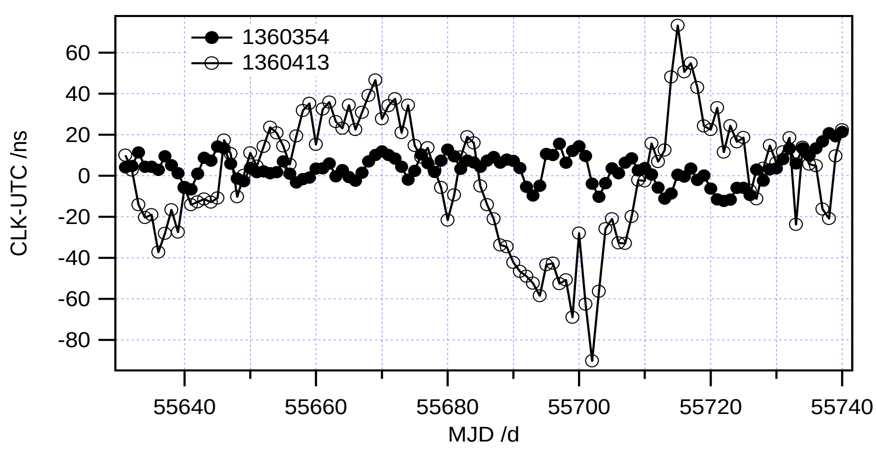

Figure 6. Recording of standard cesium clocks 1360354 and 1360413.

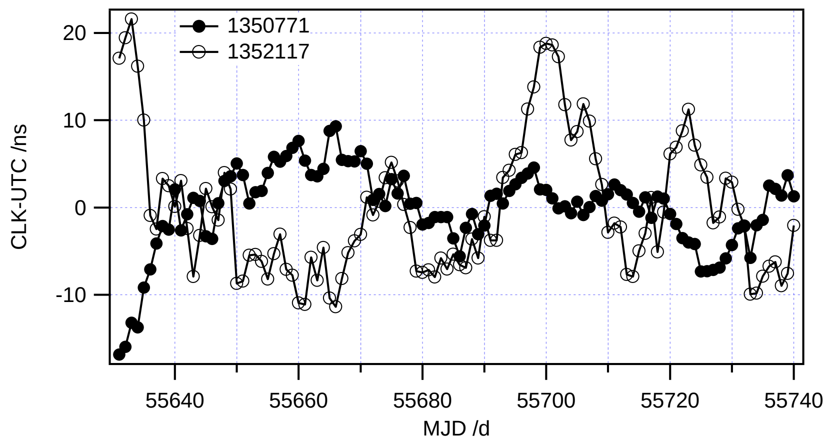

Figure 7. Recording of high performance cesium clocks 1350771 and 1352117.

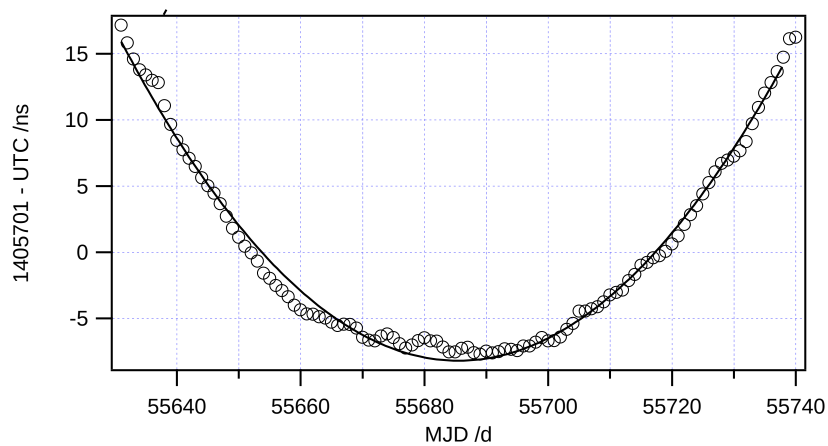

Figure 8. Recording of hydrogen maser 1405701 (drift included).

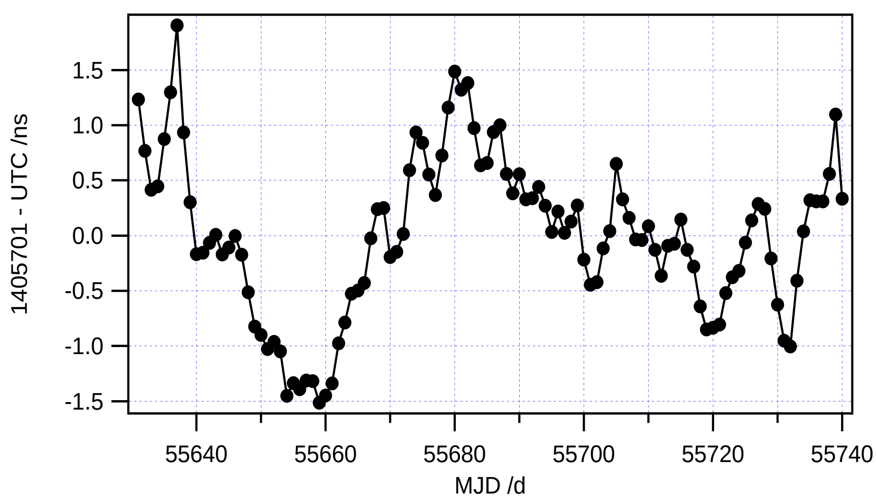

Figure 9. Recording of hydrogen maser 1405701 (drift removed).

CONCLUSION

The recent commissioning of the "production" ART system is the conclusion of a long development which started in 2002. From the computer programming point of view, the ART system is quite complex. It is a distributed system which implies continuous, seamless, IP communication between a DB server, several RT systems, a pair of MMS's and the user interface. The development effort was substantial.

In the future, we intend to keep the same basic system architecture for many years to come. This architecture is very flexible and will allow the evaluation and implementation of new algorithms (steering, time scales), as needed, with little supplementary programming efforts.

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