EXECUTIVE SUMMARY REPORT

PULSAR TIMESCALE DEMONSTRATION

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1.0	20/09/2019	9	Initial version of the Document delivered for FR milestone.

1. EXECUTIVE SUMMARY

1.1. INTRODUCTION

Coordinated Universal Time (UTC) is now the world's atomic time system, derived from the International Atomic Time (TAI). Both of these are commonly referred to as 'paper time scales', as they are not physically or instantaneously realized. TAI is computed by the Bureau International des Poids et Mesures (BIPM) in Paris using data from an ensemble of atomic clocks located at many National Measurement Institutes (NMIs) and other timing institutes around the world. The use of many clocks and an effective average of the data provides the high stability of TAI.

Leap seconds are inserted into TAI to produce UTC, which has the stability of TAI but is linked to the rotation of the Earth. UTC is evaluated a posteriori by the BIPM and published monthly as offsets from the UTC(k) reference time scales of the NMIs in the Circular T. Today, the different laboratories produce physical representations of UTC, which realize the SI second.

As can be noted, the world's timekeeping is generated based on the SI definition of the second, and is mainly dependent on commercial atomic clocks and caesium fountains for their realization. Other time scales, autonomously generated, can be built by means of other highly stable elements, such as pulsars and can be useful for the monitoring of the atomic time.

Pulsar measurements, i.e. measurements from heavily dense celestial objects emitting radiation in pulses, can be used to realise both physical and paper time scales.

The objective of the PulChron project is to demonstrate the effectiveness of a pulsar timescale for the generation and monitoring of navigation and time in general. Within the PulChron project, two different timescales based on pulsar measurements are envisioned, one being a real time physical timescale and another one being a "paper timescale".

In the physical timescale, radiotelescope measurements from pulsars are used to steer an active hydrogen maser to generate the new timescale. While in the paper clock, pulsar measurements are combined together with clocks from different stations and satellites, to realize a timescale which is expected to be the most stable one.

Historically, a timescale built with pulsar measurements have been less stable than the ones built using atomic or optical clocks in the short term, but could be competitive in the very long term. By using a combination of the best pulsar measurements, made available by the European Pulsar Time Array (EPTA) telescopes, the PulChron aims at pushing the limits of stability of the newly generated pulsar timescales.

The PulChron project has been developed in the frame of NAVISP (Navigation Innovation and Support Programme), an ESA programme aiming at fostering innovation in the PNT field while supporting industry and ESA member states interests. In this context, it is considered interesting to demonstrate the implementation of a "real time clock" and a "paper time scale" based on pulsar measurements for PNT monitoring.

1.2. PULCHRON ARCHITECURE

The PulChron is a complement to the Galileo Time and Geodetic Validation Facility (TGVF) operated at ESTEC, the technology centre of the European Space Agency (ESA) in Noordwijk, The Netherlands. The PulChron is a set of software and hardware components aimed at processing measurements from pulsars and to use the information they provide, together with the information from physical clocks, to generate a stable time scale, both in the short and in the long term.

This objective is achieved in parallel using two means: 1) a physical time scale, by steering the output of a hydrogen maser at ESTEC with the information provided by the pulsars, and 2) a paper time scale, through a composite clock which combines measurements from pulsars and estimations of satellite and station clocks from an Orbit Determination and Time Synchronization (ODTS) process. The overall architecture of the PulChron is shown in Figure 1-1.

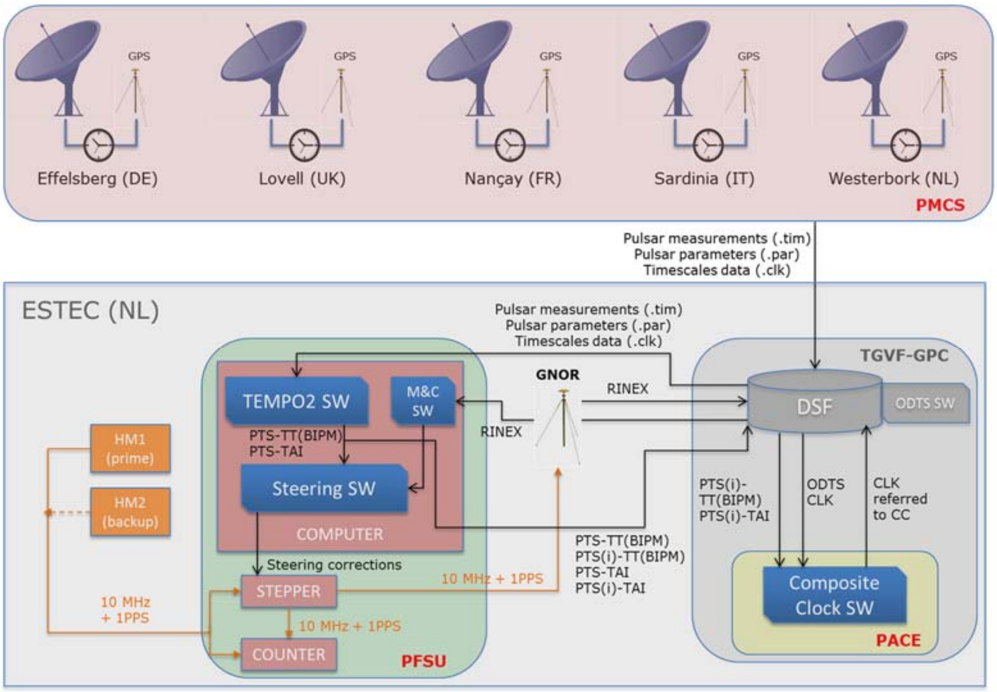

Figure 1-1: General architecture of the PulChron.

The physical time scale is based on the primary maser at ESTEC, which is steered in a stepper with the steering corrections needed firstly to correct the frequency drift of the clock and secondly to align the resulting time scale to the pulsar time scale (PT). Therefore, two different rates of steering corrections are expected, one every day to correct the drift and another one when the pulsar measurements are available, typically every 30 days. This approach should generate a time scale aligned to the definition of the second and keeping a good stability both in the short and in the long term.

The paper time scale is based on a set of clocks estimated in the TGVF's Orbit and Synchronization Processing Facility (OSPF), which implements the ODTS algorithm. In principle, any set of clocks could be used, but aiming at an overall greater stability, the composite clock should use larger weights for those clocks with a better stability. Even if the composite clock cannot be run on a real-time basis, the paper time scale could be understood as an assessment of the maximum stability that can be achieved with a combination of clocks and pulsar measurements. The composite clock uses the historical information from the estimated clocks and all the available pulsars, so it would be expected to obtain a better performance than the steered time and will likely lead to a redefinition of the SI second in the future.

The architecture of the PulChron is based on separate modules which are only connected through the TGVF archive (called the DSF, for Data Storage Facility) as can be seen from Figure 1-1. In particular, the following modules are included:

- **Pulsar Measurement Collection System (PMCS):** It collects the information and measurements from pulsars, coming from a network of telescopes.
- **Pulsar Frequency Standard Unit (PFSU):** It implements the generation of the physical time scale by steering the output of a hydrogen maser.
- **Pulsar Augmented Clock Ensemble (PACE):** It implements the generation of the paper time scale by including the clocks and the pulsar time scales in a composite clock.

1.3. FINAL RESULTS

The PulChorn element installation was performed in November, 2018 and the beginning of the Operations was on December of 2018. All the tests in the acceptance review were passed and the three different elements of the PulChron were compliant with the requirements. After the Acceptance review, at the beginning of December 2018, the different elements have been running operationally during the experimentation phase. In the following Figures, the results after 8 months of experimentations are presented.

Since December 2018, the PFSU has been running autonomously and without failures for 10 months at the moment of writing. The PFSU can be considered the most innovative output of the project, as it is the real time realization of the Pulsar Timescale, based on the steering of a Hydrogen Maser, to align it to the pulsar measurements. This type of architecture have not been previously tested to the best of our knowledge and should provide a timescale usable on a real time application, and including a stability in the long term, rivalling the best atomic timescales generated on earth (i.e. TAI and UTC).

In Figure 1-2 we can observe the deviation in phase of the Pulsar Timescale (in red) with respect to UTC as reported in the circular T. We can see from the beginning that the frequency of the PT and the one of UTC is not fully aligned, hinting at inaccuracies of the calibration or changes in the nominal behaviour of the clock. Nevertheless since the Pulsar measurements have an arbitrary frequency this difference with respect to the clock was maintained throughout the experiment, increasing the phase offset between timescale. Additionally we can see how this frequency seemed to change again around MJD 58600, and this change we attribute to another frequency change in the clock behaviour. In order to perform a fair comparison, we remove the frequency offset and drift between timescales and generate the curve in yellow.

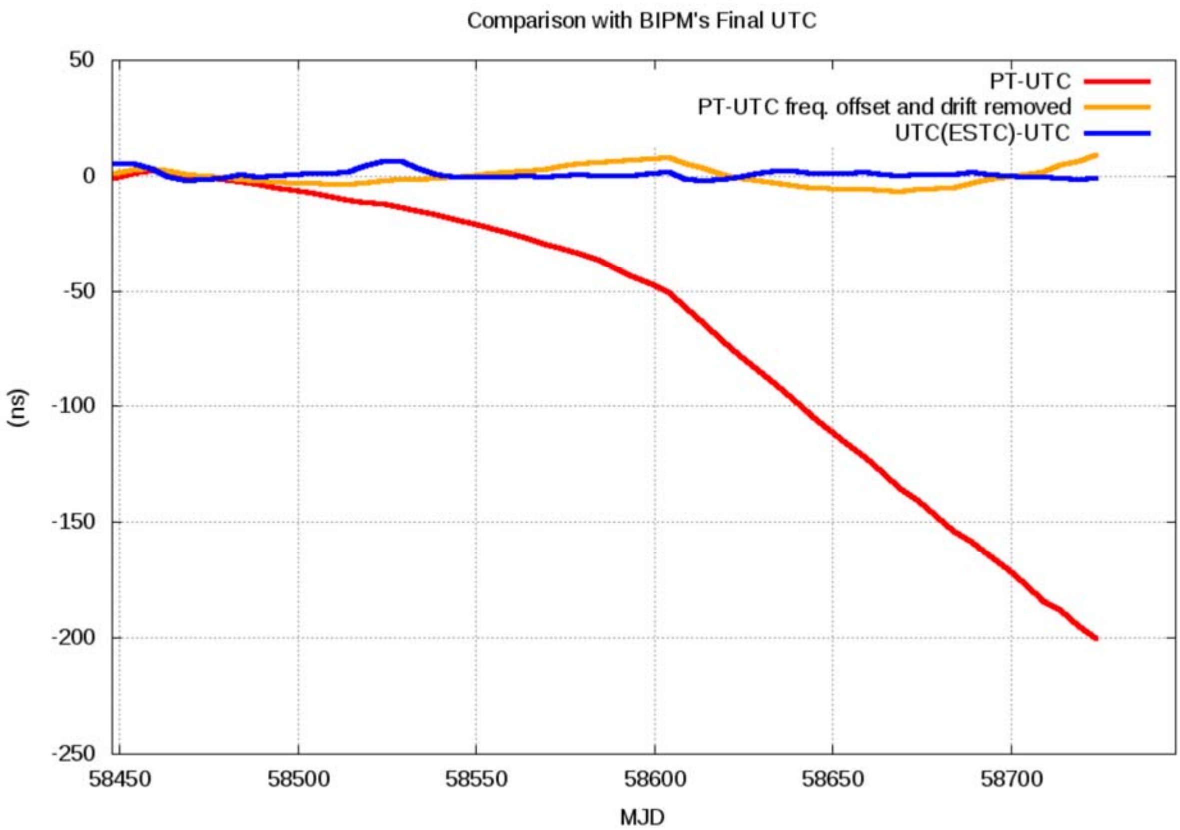

Figure 1-2 Phase Difference between Pulsar Timescale, UTC(ESTEC) and UTC

In Figure 1-3, we can observe the zoomed version of the plot, focusing on the timescales with removed frequency drift and offset. In this case we can see how the stability of PT is a little bit worse than UTC(ESTEC), having maximum deviations of 7 ns. Nevertheless, if we remove two different frequency offsets, before and after MJD 58604, we observe that the stability of the timescale is highly improved. This result also support the suggestion that the clock might have changed its frequency slightly.

Finally, in Figure 1-4 we can observe the Allan deviation of the different timescales, and we can clearly see the benefit of removing two different frequency offsets. Finally, regarding PT it seems like the scale is working properly, and will naturally deviate to UTC due to the different frequency of the pulsar and the calibration inaccuracies. Nevertheless the short term stability of the scale will be provided by the physical clock used to generate the reference frequency, and thus it can be affected by external elements to the PulChron.

In any case, to really draw conclusions regarding the long term behaviour of a real-time implementation of a timescale based on clocks and pulsars, the Pulchron experiment should be left running for several years at the minimum. The operations of the PulChron have been totally autonomous, hinting at possible long term operations without much need of human intervention.

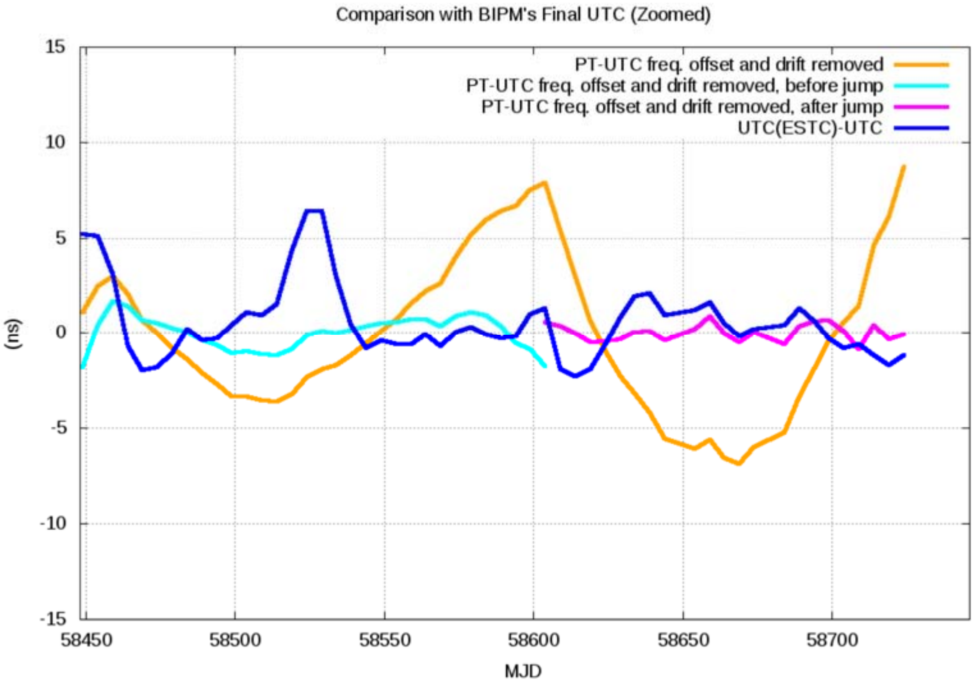

Figure 1-3 Zoomed version of Figure 1-2. Additional lines included for removal of the fit, before and after the detected jump.

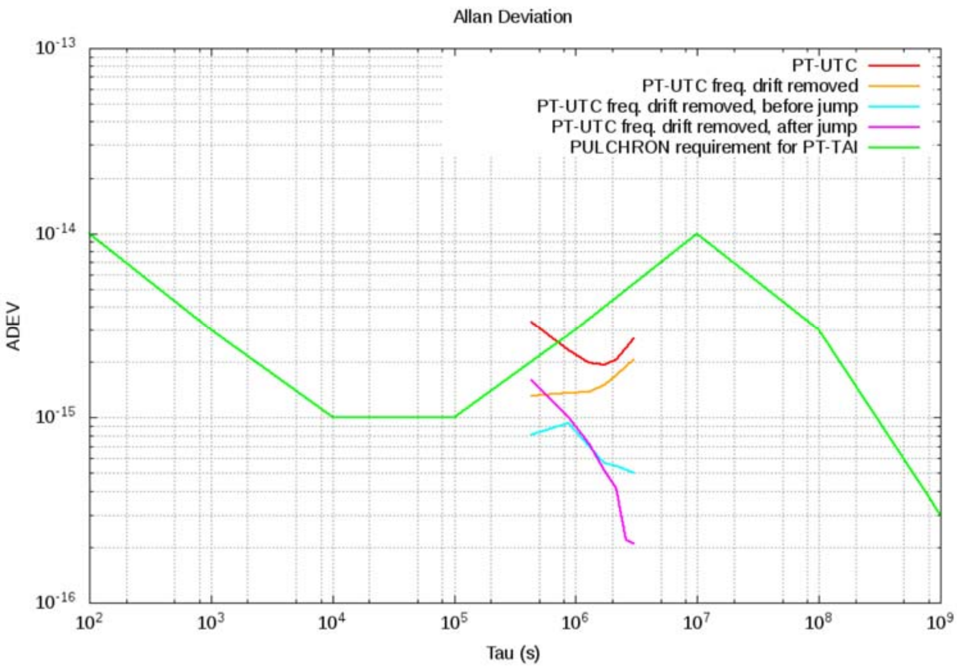

Figure 1-4 ADEV of PT, with version for before the frequency jump and after

On the other hand, another output of the PulChron project is the realized paper timescale, combining satellite and on-ground clocks, together with the pulsar measurements to form a very stable timescale. In this case, the composite clock algorithm was fully adapted to include the pulsar measurements as inputs, and combine them with other clocks.

During the composite clock development we found that one of the problems of a composite clock with pulsars and clock, was the combination of the different frequencies of each of the elements and to fix a reference point. Each of the elements have a particular frequency, which, when combined, generates a totally arbitrary frequency which is not aligned to the definition of the second, and thus will variate greatly with respect to the earth timescales. In order to maintain autonomy to atomic timescales, we steered the output timescale to the mean pulsar frequency, and thus we are able to observe the real instability of the composite clock output.

The composite clock algorithm inside the PACE element has been processes for a period of thirteen months, generating the scale using several pulsar measurements and physical clocks. The input distribution was 50% allocated to pulsar and 50% allocated to clocks in order to have a timescale representative of combination of the two types of inputs. In Figure 1-5 we can observe a comparison of the phase offsets between the final Composite Clock (CC) algorithm, the steered version to the pulsar mean frequency (CCs) and GNSS time.

From the plot, we can observe how the CCs is correctly steered to the mean pulsar frequency (PTS), while CCs is deviating from GNSS time due to its intrinsic differences in reference frame. Nevertheless, the timespan of the results is still too small to draw any conclusion on the long-term stability of such scales, which will be the main contribution of the pulsar measurements to such a composite clock algorithm.

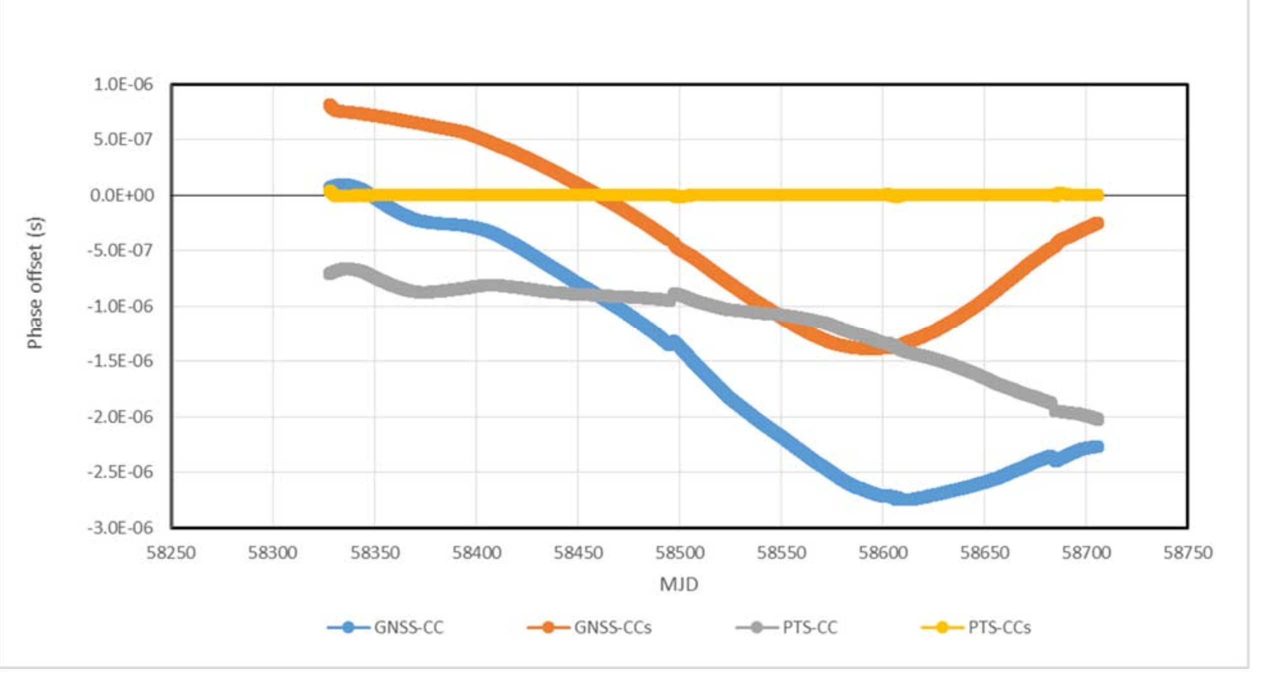

Figure 1-5 PACE timescales comparing against GPS and PTS

1.4. CONCLUSIONS

In conclusion, during the PulChron we have advanced on the research of pulsar timing, maintaining always the objective of autonomy and independence from atomic timekeeping as normally applied for earth timescales. In particular, we have enabled a new data-collection of pulsar measurements, led by the University of Manchester and their collaboration with EPTA, which will hopefully foster the use of pulsar measurements in the future. In a positive remark, the new pulsar measurement seem to have a much better quality than previous data from previous efforts.

Additionally we have created the first real-time fully autonomous timescale based on Pulsar measurements, which have been running automatically for 10 months and is prepared for long experimentation periods. Finally, a composite clock algorithm has been adapted to accept both clocks and pulsars measurements, being able to generate a paper timescale aligned to the mean frequency of the pulsar rotation.

The main limitation of the performance of the timescales are related to the stability of the atomic clocks, and their big impact in performance on such a short testing period. The benefit of the pulsar information is expected to be relevant in the long term stability with Allan deviation times longer than one year. In order to measure these points, several years of experiment should be averaged and thus careful considerations should be taken for maintenance operations and robustness to hardware failures.

The PulChron and its pulsar timescale realizations might renew the interest in pulsar timing and navigation, considering the quality of the measurements obtained during the project, and their availability as one of the first products available in the GSSC (under previous authorization of the UoM).

One of the major lesson learned during the project is the dependence of the real-time timescale generation to the behavior of the clock in the current implementation. As you need to do a-priori calibration, and to align the clock to the deterministic model, the stability of the scale, in particular in the short term can be totally dependent to clock changes with respect to the a-priori model. Even if the pulsar measurements would be able to detect and correct for the frequency difference, as the amount of noise the scale has is too big (several hundreds of ns), it takes a big phase difference to detect the frequency and correct for it. In the current experiment we expect to see the correction applied by the pulsar to come in place during the next year of the experiment.

Two different approaches are proposed for future implementations, one is to run several clocks (at least three) in parallel and steer each of them to a common pulsar timescale. With this we could be able to detect frequency jumps and clock misbehavior and correct the effects in the long term. Another possibility is to use the value of the comparison observed by the GNSS receiver (PT vs GNSStime), in order to detect jumps using this reference scale. The main limitation in this implementation is the clear dependency over other timescale for correcting misbehaviors.

The two proposed solutions could be alternative implementations for future realizations of real-time pulsar based timescales. The modification are not targeting the processing system and methodology, as these have been thoroughly analyzed and seem to be working correctly. As the pulsar measurements improve in quality, the fidelity inside the filter can be increased, and thus a more proactive design of the filter can be considered (relaxing some of the process noise assumptions).

Potential changes in the PACE (composite clock) might be summarized as that the pulsar measurements are, at the moment, noisier than other physical clocks and thus, in order to force a composite clock mixing the two types of measurement one has to play with the weights associated to each group of clocks. If the pulsars are given a weight that is comparable to the one of the clocks, the resulting timescale will have high short term noise, and we are not able to tell at the moment, if at long term the contribution would improve the stability. Additionally, there is the problem that, to have a fully independent timescale, the resulting timescale will have a totally arbitrary frequency and drift, thus we should make a steering of this frequency to a predefined reference timescale.

Finally, an additional step for increasing the robustness has been identified in that the stepper does not include possibilities for a dual power supply and thus the continuity of the scale can be degraded. Actually, during the project a shutdown of the rack had to be performed, and thus continuity was lost for several hours. Fortunately, due to the programmed event the recovery procedure was successful and no degradation is observed in the scale. For this reason the connection of the PulChron elements to an external battery (e.g. UPS) should be considered, especially due to the very long duration of the intended experimentation.

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