Development and Validation of an External GPS Time Synchronization for Robotic Total Station Control

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Abstract

Robotic total stations (RTS) offer great potential for use in the context of diverse kinematic measurement processes. However, a central challenge is the accurate and reliable combination of the polar measuring elements of the RTS with a higher-level global time reference. Global positioning system (GPS) time or coordinated universal time (UTC) are available for this purpose, but cannot be directly linked to the instrument. This paper presents a flexible concept for external synchronization of an RTS by means of an additional microcontroller. The developed synchronization box relies on extended communication commands of the instrument manufacturer's *Measure & Stream* application and is supposed to account for all significant offsets and latencies without additional laboratory calibrations. Using an independent validation procedure, absolute temporal offsets to a UTC-triggered laser tracker-based reference solution with superior accuracy are examined. This revealed a significant offset of 55 *ms* of the developed synchronization solution compared to the high accuracy reference, which is comparable to the determined latencies of related work in the context of laboratory calibrations. It is shown that further long-term investigations of the synchronization box are required and in particular the reliable and precise operability of the *Measure & Stream* application should be further investigated with a dedicated experimental setup.

1 Introduction

1.1 Motivation and Objective

Robotic total stations (RTS), with their flexible automation capabilities, represent a powerful opportunity when it comes to reliable, robust, and precise acquisition of kinematic measurement processes. This can be, for example, the realization of reference trajectories, the geodetic monitoring of infrastructures or machine control and guidance applications. Also in the context of developing kinematic multi-sensor systems (MSS), the measured position observations from an RTS are often used as an important source of information for validation purposes or directly as a contribution to localization estimation. This is mainly due to the flexible application possibilities of the instrument both indoors and outdoors as well as by the utilization of long target ranges. Up to now, global navigation satellite system (GNSS)-based methods have often been used for the aforementioned application scenarios. These methods are superior in terms of range and can be used with less effort, but they are limited to outdoor areas. The achievable uncertainty parameters are highly dependent on the prevailing satellite constellation and availability, are subject to influences such as multipath, and exhibit overall higher measurement uncertainties compared to RTSs. Application of RTSs is not entirely free of limitations either. Besides possible restrictions, such as a limited measurement frequency ($< 20\ Hz$) or the continuous line of sight to the reflector, the realization of a time reference to a higher-level time base is a key challenge. In contrast to other geodetic measuring instruments, current RTSs do not provide a trigger in- or output, which would allow a simplified time synchronization. In addition to the frequently necessary realization of a spatial relation between the measured object, instrument and a suitable (reference) coordinate system, it is also essential, at least in the case of kinematic measurement processes, to establish a physical reference to a superordinate time system (temporal reference frame) with the aid of synchronized time stamps (HENNES et al. 2014). This indispensable necessity exists whenever multiple RTSs are used simultaneously or the observation information of an RTS is to be fused with measurement data from other sensor types (e.g. inertial measurement unit (IMU) or GNSS).

Under the impression of modern sensor technology of current MSSs, global positioning system (GPS) time or coordinated universal time (UTC) is the method of choice for a temporal reference frame. These high-precision time sources can be accessed via network time protocol (NTP) servers or GPS. The first requires a stable network connection, which is not always available, especially in outdoor environments. In contrast, GPS signals can usually be received worldwide and do not have any special additional hardware requirements. If only the pure time component is of interest, simple low-cost antennas are sufficient. Even indoors, the GPS signals can be used for synchronization, provided that a GPS antenna mounted outdoors is accessible by cable. However, a direct connection between these global time sources and the measured quantities of an RTS is not provided by the manufacturers. Instead, the reference of the distance and angle measurements is only realized to an independent internal sensor time, which, however, does not meet the described application purposes with regard to highest quality requirements. Depending on the speed of motion and type of the observed kinematic process, an inaccurate temporal referencing directly affects the quality of the position determination. The range of possible motion velocities of a reflector to be tracked is large. Both slow velocities for monitoring tasks of $< 0.01\ m/s$ as well as the tracking of a slowly moving vehicle at $5\ m/s$ are basically potential fields of application with an RTS. However, this results in accuracy requirements for the synchronization of at least $100\ ms$ up to $0.5\ ms$, if we assume a required position accuracy in the millimeter range. For this reason, an extra controller is required, which is synchronized with UTC and can thus set the original measuring elements of the RTS in relation to it. There are two key aspects to consider. First, the precise, reliable and robust synchronization of the controller with UTC, which is generally independent of the RTS itself. Secondly, it is about the actual acquisition of measurements as well as the communication between the RTS and the controller with the lowest possible and constant latency. There are already some approaches and studies that deal with these two challenges (e.g. GOJCIC et al. 2018, THALMANN & NEUNER 2021), which will be discussed in the following Subsection 1.2. However, all methods known to the authors rely on the need for separate field and laboratory calibrations, which involve additional effort. Furthermore, validation of the available approaches with a fully independent reference solution using sensors of superior absolute accuracy has not yet been done.

For this reason, an efficient method for precise synchronization of a Leica Geosystems RTS using GPS time was developed at the Geodetic Institute Hannover. In relation to the limited measurement frequency of an RTS, we are focusing initially on motion velocities below the walking speed of 1 m/s for the time being. In particular, the monitoring of robotic systems in the direct surrounding of people or monitoring tasks with low kinematics are to be mentioned here as potential fields of application. However, the long-term goal should be to ensure that reliable use is also possible for velocities up to 5 m/s and thus a generally applicable solution exists. Therefore, the current limitations of the system regarding synchronization capability have to be evaluated. The realization includes both software programming and hardware implementation and can be easily reproduced. The final prototype is a user-friendly, weatherproof and flexible synchronization box with visual feedback, which is connected to the RTS and a GNSS antenna. The basis is a microcontroller inside a 3D-printed box, which continuously processes the time signal from a GPS board and provides it as a reference server for the system time via NTP. For the RTS internal synchronization as well as the time-traceable communication between RTS and controller, software applications provided by the manufacturer are applied. This is intended to avoid time-consuming laboratory calibration. The extent to which this is possible must be verified. The use of the synchronization box was empirically tested in several experiments and validated on a circular trajectory with an externally triggered laser tracker (LT) as an independent higher-level reference solution, which is new in this context.

In the following subsection, thematically related work and practice-relevant application scenarios are mentioned. Section 2 presents the developed concept for synchronizing an RTS and addresses the realization of the synchronization box. The validation of the in-house development is shown in Section 3 using a representative data set. A summary, along with an outlook on future work, conclude this paper in Section 4.

1.2 Related Work

Several authors have already dealt with the synchronization of RTSs in terms of different measurement and tracking applications. In the following, we will briefly present and differentiate some relevant work associated with our own synchronization development.

The fundamental need for reliable and accurate synchronization solutions for RTSs is demonstrated by various application examples. In the context of geodetic monitoring and control of civil infrastructures, RTS have been used for a long time. Due to the increasingly complex requirements (either with regard to the number of parameters to be determined or their uncertainty), a wide variety of MSSs are being used more and more frequently. As an example, the work of HESSE et al. (2021) can be mentioned, who use a multisensor platform operating on water to detect and inspect water infrastructure facilities, whose position is additionally determined continuously from land using an RTS. In LIENHART et al. (2017), an RTS is used in combination with an accelerometer to monitor displacements of a pedestrian bridge under different loads. Other application scenarios include rial track surveying (DENNIG et al. 2017), object tracking (EHRHART & LIENHART 2017) or the validation of MSSs by means of reference trajectories (HESSE & VENNEGEERTS 2014).

For reliable and accurate results, the temporal synchronization of the observed quantities is an essential prerequisite for all the application examples mentioned. The key challenge for the synchronization of an RTS is the interaction of all internal measurement processes running within the device each with its time reference. STEMPFHUBER (2004) discussed in detail the different measuring times such as automatic target recognition (ATR), horizontal and vertical angle measurement as well as distance measurement (as an excerpt of all subsystems to be considered). In DEPENTHAL (2009), a 4D calibration system is developed on the basis of a rotating arm, which can also be used to determine the internal latencies of an RTS. The contribution by KLEEMAIER (2018) also addresses the problem of time synchronization of an RTS, describing the available time stamps of modern RTSs from Leica Geosystems. Possibilities for external synchronization of the measurement data are discussed on a theoretical level. In addition to the popular use of the GeoCOM interface for communication, reference is made to the data stream of the *Measure & Stream* application, which enables automatic synchronization of the internal time stamps of the sensor board with the time instants of an external controller.

The simultaneous use of multiple RTSs is investigated in KEREKES & SCHWIEGER (2018) with the goal of being able to ensure the uninterrupted tracking of a moving reflector from different points of view. In this regard, the authors explicitly point out the incompletely solved challenges concerning the synchronization between multiple RTSs. For the validation of a robot-based MSS, three RTSs are used in combination in VAIDIS et al. (2021) to determine the full 6 degrees of freedom of the robot motion as a ground truth trajectory in adverse GNSS environments. The actual synchronization is done centrally on the embedded computer on the robot, thus there is no reference to a global time system. Furthermore, GOJCIC et al. (2018) present an approach for real-time synchronization of multiple RTSs, which is independent of the prevailing environmental conditions and does not require additional hardware. For this purpose, they propose a method for calibrating the internal sensor time, which depends on the respective ambient temperature. Calibration functions are established for this purpose using a climate chamber to correct drift rates such that, in conjunction with cross-correlation, synchronization between two spatially separated RTSs occurs after a time period of eight hours better than 50 ms.

In THALMANN & NEUNER (2018), an approach based on NTP for synchronization of multiple RTSs in an environment with GNSS absence is investigated. The performance in terms of synchronization quality and stability of NTP is compared to a synchronization solution using GPS time (which serves as ground truth). A synchronization quality in the microsecond range is possible even via WLAN, but only refers to the level of the controller (Raspberry Pi) and does not take into account communication with an RTS and its sensor-internal influencing factors. The authors continued their research in THALMANN & NEUNER (2021) and present an approach for the temporal calibration and synchronization of an RTS. Based on a WLAN connection, a precise temporal reference frame is established, which allows spatial flexibility of the instruments. Overall, the authors demonstrate a synchronization quality of 0.2 ms in the context of a test setup. The solution consists of three aspects. A microcontroller (Raspberry Pi) is synchronized via NTP. Then, a synchronization between GeoCOM response at the controller and the GeoCOM sensorboard timestamp of the RTS is performed. For this purpose, a synchronization initialization routine is performed on a static prism directly before (and, if necessary, after) a measurement campaign. The offset between controller clock and internal RTS clock is approximated with a linear model and applied in the further course. Remaining intrinsic synchronization parameters related to angle and distance measurement as well as general latency times in this context are determined and considered individually for the instrument used. For this purpose, the corresponding parameters are calibrated in advance in the laboratory with a kinematic motion model using a robot arm. Reproducible offsets of approximately 65 *ms* (for system and distance latency) and approximately 7 *ms* (for angular latency) are determined over a period of 6 months for a Leica TS16.

In HESSE et al. (2021), an approach to synchronize an RTS based on an external synchronization box is presented, which is comparable to the concept presented in this paper. However, the authors neither go into technical details nor validate their solution. In particular, the lack of validation with an independent, absolute reference solution that is superior in terms of accuracy is not present in all previously mentioned methods for external synchronization of an RTS. In addition, all approaches, except HESSE et al. (2021), require a corresponding individual calibration of the RTS in advance or after the actual measurement. In contrast, the solution presented in the following is intended for automated calibration of the synchronization without additional field and laboratory measurements. This applies both to the internal measuring time stamps of the RTS and to the communication between RTS and controller individually for the corresponding device. The basis for this is the use of extended GeoCOM commands of the *Measure & Stream* application for RTSs from the manufacturer. The extent to which this is valid and reliably applicable in its entirety must be critically assessed. Therefore, precision and accuracy of the synchronisation solution are examined on the basis of the time-synchronized reference solution by a LT using a circular reference trajectory.

2 Concept for Synchronization

To synchronize the original measuring elements of an RTS to a global time reference, several relevant time frames have to be considered and related to each other. As mentioned in the introduction, the aim of our concept is to realize a superordinate time reference to the worldwide valid UTC. For independence from available Internet connections, the GPS time is to be used for this purpose, which has a constant offset to UTC depending on the respective valid number of leap seconds. However, since these time systems cannot technically be linked directly to an RTS, an additional controller must be used. Therefore, the use of a microcontroller is recommended, due to its small size, versatility and low purchase price. In the following, the relevant time systems are introduced and the realization of the synchronization box is described.

2.1 Relevant Time Systems

The RTS itself contains various internal time systems that must be considered. Besides the clock of the operating system (OS) used (Windows CE in this case), this is in particular the relative time scale of the sensor board. This time reference basically refers to the start time of the instrument and counts up the past milliseconds since start (SSS). To obtain a set of observables (distance, horizontal and vertical angle), the results of the individual subsystems are combined. The most essential for this are the two angle readings, the distance measurement of the EDM and the deviations of the ATR. All these separate measurement processes usually take place asynchronously and refer to an individual point in time. As long as the observed reflector is static, this circumstance does not matter. In kinematic applications, however, this fact is of great importance to obtain precise measurement results, depending on the speed, shape and distance of the movement. In addition, so-called latencies can occur between the respective measured value acquisition and the availability of the measured result, which negatively influences an external synchronization. A Raspberry Pi microcontroller is used as the external control unit for our synchronization box, which has its own system clock.

A highly precise primary civil time source is UTC, which is defined by stable atomic clocks as an international standard via the International Atomic Time (TAI). It is independent of local time zones and is irregularly adjusted to universal time (UT1), taking leap seconds into account. There is a direct connection to the GPS time, which is also defined via the TAI. By not taking leap seconds into account, it is 18 seconds ahead of UTC (valid for 2022). The GPS time can be received by means of GNSS messages through an antenna-receiver combination. Using National Marine Electronics Association (NMEA) sentences, the absolute (but rather inaccurate) time information can be obtained. The precise relative time information, with deviations in the nanosecond range (U-BLOX 2020) compared to UTC seconds, is obtained via the additional pulse-per-second (PPS) for the start of each UTC second. In combination of NMEA and PPS the precise and absolute GPS time is obtained (KOO et al. 2019).

2.2 Realization of the Synchronization Box

The actual technical implementation of the developed synchronization solution is based on three aspects. As a basic prerequisite, the individual RTS-internal sensor time systems must be synchronized with each other so that a set of observation parameters refers to a consistent point in time. Accordingly, this includes the determination of latency times between the individual subsystems as well as the consideration of their possible temporal variation. The second aspect is to synchronize the system clock of the controller with UTC and keep it stable. Finally, the NTP offset between the RTS clock and the system clock of the controller must be determined and possible time variations must be identified and accounted for. The individual parts are described in detail below.

RTS-internal Synchronization: All individual measurement time points of the subsystems provide a temporal reference using SSS, the relative time scale associated with the start of the instrument. The use of the *Measure & Stream* application on the RTS is intended to determine the existing internal sensor latencies between the above mentioned subsystems and, according to the manufacturer, provides a consistent temporal reference depending on the prevailing internal conditions (LEICA GEOSYSTEMS 2022). For the later streaming of the individual measured values, the time reference to the relative RTS clock is available with millisecond accuracy.

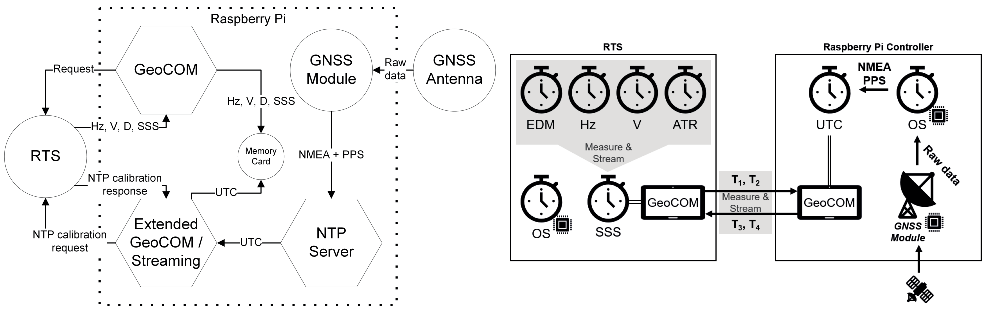
Synchronization of the Controller with UTC: For receiving GNSS messages a uBlox GNSS module with LEA-M8T chip is connected to the Raspberry Pi 4 controller via GPIO pins. This receiver has a timing accuracy in the nanosecond range. A GPS Deamon (GPSD) is used to collect and process the GNSS messages. The NMEA and PPS information obtained in this process are configured as an authorized time source for the controller via NTP. The system clock of the controller thus follows UTC and is continuously updated and stabilized via the PPS hardware signal.

Determine NTP Offset Between the RTS Clock and the System Clock of the Controller: The most complex part involves the timing consideration of the communication between RTS and controller. Prevailing offsets and drifts depend strongly on the hardware used and can vary individually as well as in time. By using the *Measure & Stream* application, extended GeoCOM commands are available, which serve to determine the actual offset and cable latency between RTS and controller. The actual determination of these crucial parameters is realized via an NTP implementation. Four time stamps T_1, T_2, T_3 and T_4 are used for this, two each referring to the RTS (T_2, T_3) and the controller (T_1, T_4). To synchronize the system time of the controller with the measurements of the RTS, the time stamps of the individual measurements are required. Therefore, in this case T_2 is the EDM time of the last measurement when the NTP command was received. T_3 is the EDM time of the next valid measurement before the response is sent. T_1 is the system timestamp of the controller when the request is sent and T_4 is the system timestamp when the response is received. With this information the NTP offset t between RTS clock and controller clock can be calculated according to (LEICA GEOSYSTEMS 2022)

$$t = ((T_2 - T_1) + (T_3 - T_4))/2. \tag{1}$$

All present network and cable related latencies are included within t. To account for temporal changes in t, its determination is re-executed every 30 seconds. Therefore, all necessary synchronizations have been carried out and the corresponding offsets are known. The observation data of each measurement (distance, horizontal and vertical angle as well as the corresponding SSS) are streamed to the controller via TCP and stored locally on a memory card. Synchronization of observation data to UTC is done in post-processing by applying the NTP offset t to each set of observation parameters to the given sensor board milliseconds. Thus, the exact local sensor board times of the measurement raw data from RTS can be brought in relation to an external absolute time information (UTC in this case).

The described concept of the synchronization box is schematically shown in Figure 1a. An overview of the relevant time systems and their synchronization is shown in Figure 1b. In addition to the hardware components, the communication paths are illustrated. Figure 2 shows the physically realized 3D-printed box with the applied Raspberry Pi 4 microcontroller and ublox GNSS module. The RTS is controlled via a user-friendly, intuitive GUI application written in Python with visual feedback, which allows input via the resistive touch-display.



(a) (b)

Fig. 1: Schematic structure of the synchronization box based on a Raspberry Pi 4 (dotted rectangle) in a). Physical sensors and components are marked with a circle and central software components with a hexagon. Main clocks and subsystems including their synchronization via *Measure & Stream* application (gray areas) between RTS and controller in b).

3 Validation

The quality of the developed synchronization box must be reviewed with regard to its accuracy, precision and reliability. Here, different aspects and influencing factors, such as the temporal stability of the internal clock of the Rapsberry Pi and the GNSS module as well as offsets during communication via GeoCOM commands, can be addressed. However, in addition to the temporal stability, the absolute time correctness of the measurement elements of the RTS provided with UTC time stamps is of particular interest in this paper. For this reason, the synchronization results of the RTS are checked with an independent reference setup. A high-precision LT is used for this purpose, whose original measuring elements can be reliably referenced by UTC. The actual experiment and the resulting findings are presented below. The synchronization box was developed with regard to the application using a Leica TS60 RTS. In principle, it will also be possible to use the box with other RTSs from Leica Geosystems, provided that the *Measure & Stream* application is available. In the following, however, we will limit ourselves exclusively to the Leica TS60 and aim for a broader application test in the future.

3.1 Experiment

A Leica AT960 LT is applied as an independent referencing capability. This high-precision sensor (3D positional accuracy in the micrometer range) has a trigger input that is used for precise synchronization. Using a trigger signal is a simple and accurate synchronization solution and differs significantly from the procedure for an RTS, which does not have such a trigger input. The procedure for the LT has been tested and used successfully in various projects (e.g. VOGEL 2020). The basic setup of this synchronization solution is shown in Figure 3. A Javad Delta GNSS receiver is the essential hardware component. It has the

(a) **(b)**

Fig. 2: Front view with touchable user interface (a) and inside view (b) of the 3D printed synchronization box with touchscreen (in the cover on the left), Raspberry Pi 4 (board in the middle), ublox GNSS module (chip on the right) and associated wiring

possibility to generate an individual trigger signal. This signal is introduced into the trigger input of the LT and triggers individual single point measurements with the corresponding frequency. On the other hand, the original trigger signal is directly reintroduced into the trigger input of the Javad Delta and the corresponding UTC information is stored with identical frequency. In this way, two files with identical number of lines are obtained at the end of one measurement, which contain the polar measuring elements of the LT in the first file and the corresponding UTC time stamps in the second file.

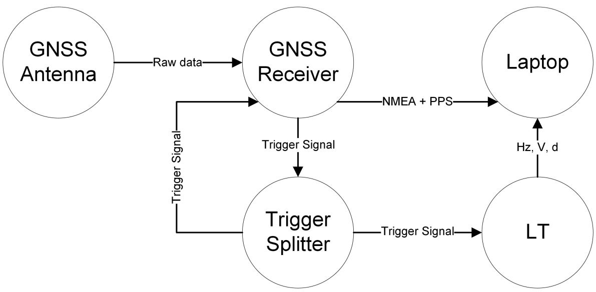
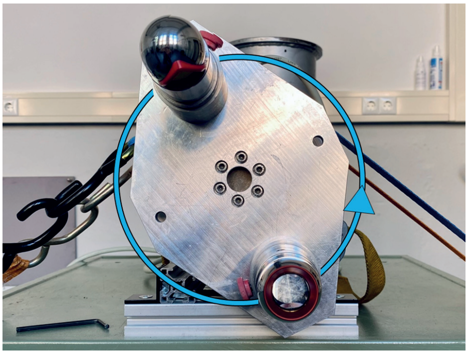


Fig. 3: Schematic setup for synchronization of LT observations with UTC

For the evaluation of the synchronization solution for the RTS, a defined trajectory has to be acquired synchronously with the RTS itself and the LT. To enable additional statements about possible temporal variations, a trajectory shape that can be reproduced as desired is advisable. Therefore, both RTS and LT simultaneously observe the uniform and repetitive motion of a corner cube reflector (CCR) on a rotating disk with constant speed. The two sensors are set up horizontally next to each other and the rotating disk is aligned at a distance of about 3 meters to ensure uninterrupted visibility at all times. As a result of the rotating disk actuator, the CCR describes a circle with a diameter of 15.55 cm. The average duration of 7.23 s for one revolution corresponds to a velocity of 0.0676 m/s. This experimental setup therefore only allows statements to be made with regard to low kinematic motion behavior. This must be taken into account, as any inaccuracies in synchronization become more evident as the velocity of movement increases. The experimental setup is shown in Figure 4. This results in two independent time series with the original observation variables of the RTS and the LT. To obtain the observations of both sensors in a common coordinate system, in total 7 control points distributed in the laboratory are measured and the 3D coordinates of the RTS are transferred into the coordinate system of the LT via a Helmert transformation. For this purpose, the original measuring elements of the RTS are first converted from polar to Cartesian coordinates. The standard deviations of the estimated transformation parameters are < 1 mm for the translations and < 0.01 $^\circ$ for the rotations.

(a)



(b)

Fig. 4: Experimental setup in a) with the RTS (background on the right) and the LT (foreground on the right) aiming at the rotating disk. Close-up of the rotating disk with CCR (bottom) and counterweight (top) in b).

3.2 Results

To analyze the possible time offset between the measurements of the RTS and the LT, its temporal behavior over a period of about three hours is investigated on the basis of the repetitive circular motion of the CCR on the rotating disk. In total, 1477 complete revolutions of the CCR were captured, which show a periodic oscillation behavior in the individual coordinate axes. However, only the coordinate axis with the most significant rate of change (Z-axis) will be discussed in the following. As an example, the resulting time series for RTS as well as LT with respective reference to UTC are shown in Figure 5a for the first 10 revolutions. The significantly different measuring frequencies of the RTS (8 ± 1 Hz) and the LT (100 ± 0 Hz) can be clearly seen. Moreover, the measurement rate of the RTS is not constant and contains gaps of different lengths at irregular intervals. In addition, a slight temporal lead of the RTS observations compared to the LT is evident.

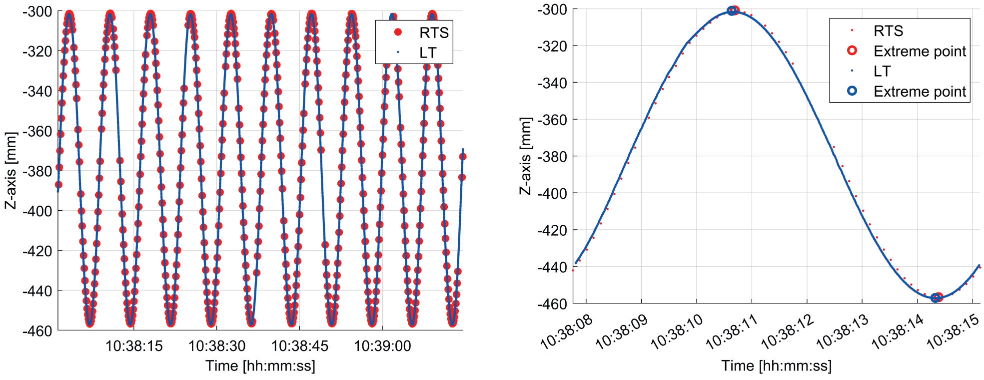


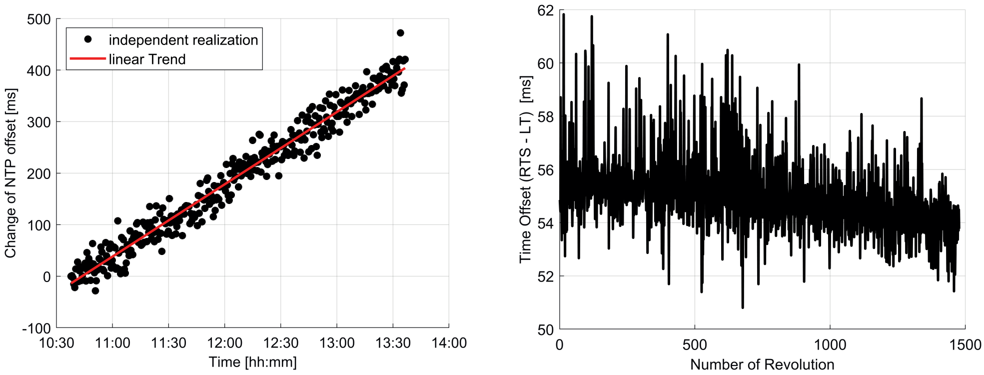
Fig. 5: Temporal course of the Z-component of the CCR for the first 10 of in total 1477 revolutions for RTS (red circles) and LT (blue dots) in a). Identified extreme points (circles) of the RTS (red) and LT (blue) time series for an exemplary full revolution of the CCR at the rotating disk using individually fitted Fourier curves in b).

To be able to determine the time offset as reliably as possible, distinctive points of each revolution are used, which can be determined precisely in both time series. For this purpose, the respective maximum and minimum peak points are used. To investigate a possible temporal variation of the offset, the 1477 revolutions are considered and analyzed individually per single revolution. Since the different measuring frequencies of the two sensors can have a negative impact on the precise identification of the extreme points, a Fourier curve

$$f(x) = a_0 + a_1 \cdot \cos(x \cdot w) + b_1 \cdot \sin(x \cdot w) \tag{2}$$

is estimated independently for each epoch (an epoch is defined by one complete revolution) for both time series. Here a_0, a_1, b_1 and w represent the coefficients and x the input parameters (time values). For the first epoch, the identification of the prominent points of both time series is shown in Figure 5b. For the sake of clarity, the fitted curves have been omitted. Also an analysis of the estimated coefficients across epochs and between RTS and LT time series is omitted here, but offers future potential for investigation to further improve the determination of the offset. The quality of the independent curve fitting is controlled on the basis of the coefficient of determination R^2. This is to ensure that only successful approximations are used for further investigation. All coefficients of determination are at least 99.98 % for all epochs. Overall, it can be stated that the individual epochs of the time series can be described appropriately with the chosen mathematical model.

Figure 6a shows the temporal behavior of the NTP offset t between RTS clock and system clock of the controller (cf. Section 2.2) during the whole measurement campaign. The individual realizations are available with a time interval of 30 seconds. A clear time drift of t can be identified over the three hours, in the amount of 39 *ppm* in total. In addition, a clear noise of the individual realizations can be observed. Independent studies have shown that the standard deviation of t for offset determinations performed in direct succession is approximately 40 ms. For the synchronization of the observed quantities of the RTS with relative time reference, the respective valid offset t is linearly interpolated and taken into account, so that a UTC time stamp is available. Based on the reliably identified extreme points, the temporal offset with reference to UTC between RTS and LT can thus be determined. The time offset is therefore estimated twofold per epoch. Figure 6b shows the temporal variation of the offset for all 1477 epochs averaged for the extreme points. In general, the offset decreases from 55.6 ms initially to 53.8 ms in the last epoch. A descending linear trend can be recognized, whereas the offset varies < 10 ms in total.



(a) **(b)**

Fig. 6: Change of the NTP offset between the RTS clock and controller clock over time. Single measurements with a time interval of about 30 seconds (points) as well as estimated linear trend with a coefficient of determination R^2 of 96.7 % (red line) are shown in a). Time offset between reference solution from LT and RTS over the total 1477 revolutions of the CCR on the rotating disk in b).

3.3 Conclusions

The validation of the developed synchronization concept shows that a significant absolute offset of about 55 ms must be expected. The responsible causes are difficult to identify. Software applications provided by the instrument manufacturer were used, which on the one hand are supposed to reliably synchronize the internal sensor time systems and on the other hand determine offset and latency between RTS and controller communication. The stability of this NTP offset is not granted even for short measurements of a few minutes, but it follows a distinct linear trend. The identification of the extreme points, as an evaluation basis of the temporal deviation from the LT reference, is reliable. For a period of a few minutes, the deviation from the reference can be assumed to be constant and within the submillisecond range. In the longer term, a linear trend must be taken into account. Overall, however, it is noticeable that the identified offset of approximately 55 ms corresponds numerically well with the system and distance latencies identified in THALMANN & NEUNER (2021) (approximately 65 *ms* for a Leica TS16). The authors determined this value in the laboratory and assumed it to be known for the actual synchronization. A comparable procedure would therefore also be appropriate in the concept presented here based on the LT reference. However, this still requires further studies that examine the behavior of the offset over a longer measurement period per se and more repetitions (short term and long term). Overall, the importance of independent validation of the synchronization solution is evident. Relying solely on the synchronization capabilities of the *Measure & Stream* application is not sufficient and can lead to significant synchronization errors in the mid-millisecond range. Depending on the velocity v of a moving reflector, each millisecond of deviation results in a position error of one millimeter (for $v = 1\ m/s$).

4 Summary and Outlook

A flexible concept for the synchronization of an RTS with GPS time was presented, which should avoid an additional calibration in the laboratory for the determination of device-dependent influencing parameters and instead exploits the extended capabilities of the *Measure & Stream* application. For its realization, an independent validation procedure for the achievable synchronization accuracy by an externally triggered LT with UTC timestamps was developed and performed. A significant offset of the synchronization solution compared to the LT reference was identified. The validation was carried out on the basis of a low motion velocity of around 0.07 m/s, so that statements on the synchronization quality for higher kinematics cannot be made at present. Since possible fields of application are certainly targeted with velocities of up to 5 m/s, the reference trajectory must be modified in this respect for validation purposes. In the future, further repetitive long-term investigations on the stability of the determined offset and modeled linear trends are necessary. In addition to the NTP offset between RTS and controller, this applies in particular to the absolute time deviation compared to the LT reference. Furthermore, a separate detailed investigation of the *Measure & Stream* application regarding its internal sensor synchronization should be performed to be able to exclude remaining latencies. In addition, the development and application of an alternative analysis method for the comparison between the RTS and LT observational data based on time series analysis to overcome residual approximation errors due to the estimation of Fourier curves is suggested. In particular, the cross-correlation method is promising and should be benchmarked against the current method. The transferability and applicability of the synchronization box to other RTSs such as the Leica TS16 and MS60 need to be investigated. The latter in particular has better tracking properties (especially higher measurement rates) compared to the TS60.

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