The Shelyak TimeBox - A Device Allowing Multi-Mode Accurate UTC Time Recordings for Digital Video Cameras

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ABSTRACT: The Shelyak TimeBox has just been released as a multi-mode, accurate, modular and portable solution for UTC timing using digital video cameras in a *Windows* environment. The goal of this article is to show the results of independent testing of the Shelyak TimeBox using described methods that measure the accuracy of UTC timestamped recordings for both featured computer and trigger modes. The results of the tests and recordings presented in this article showed that the Shelyak TimeBox was able to allow accurate UTC timestamped recordings using digital cameras up to the millisecond (ms) precision. The modular design of the Shelyak TimeBox separates the UTC timestamping from the recording camera, allowing the use of the last-generation, sensitive and low noise CCD, EMCCD and CMOS image sensors for occultations and other astronomical phenomena requiring precise UTC timestamping.

Introduction

The timestamping of astronomical occultations and other astronomical phenomena need to be done in an absolute time scale in order to allow collaborations between different observers around the world. The timescale chosen is the Coordinated Universal Time (UTC) that is the primary time standard regulating clocks and time [1]. Stellar occultation by Solar System Objects (SSO) is a proven method used to determine the size, 3D shape, topology and accurate positioning of asteroids including their satellites [2]; in addition, stellar occultations are used to improve astrometry of asteroid orbits by linking their position to the *Gaia* coordinates of a star at event epoch [3], to measure occulted star size, to detect multiple star systems, to detect asteroid satellites, to produce accurate TNOs ephemeris [4], to provide information of the atmospheric pressure of TNOs and planets [5], and recently, to discover the presence of rings around minor planets of the outer solar system [6].

Most amateur astronomers use a timing system that stamps the UTC time in every frame of an analogue video recording using the Composite Video Baseband Signal (CVBS) standard and devices that use either a radio clocking signal as DCF77 or a Global Navigation Satellite System (GNSS) receiver (Black Box, Kiwi device, TIM10, IOTA-VTI). This system was validated by the International Occultation Timing Association (IOTA) community for years and used by many observers for almost twenty years [7].

Most observations are still made using analogue video cameras coupled to analogue-to-digital converters producing digital DVI or SER files. However many observers wish to use the many advances in image quality that new digital video cameras offer, including bit depth increasing from 8 bits to 12-16 bits among others. The last generation of the most sensitive and low noise CCD, EMCCD and CMOS image sensors are embedded in digital cameras. CMOS image sensors are digital as the sensor chip itself produces a digital output compared to the analogic one produced by the CCD arrays. Last generation CMOS image sensors possess sensitivity and noise levels comparable or above to those of the best CCD sensors, without its major limitations like the low frame rate and high costs of production [8]. The evolution of CMOS image sensor capabilities is likely replacing the CCD sensors thus favouring the development of affordable highly sensitive/low noise digital video devices now and in the near future.

In order to use digital cameras for the recording of astronomical occultations, these systems' UTC timing has to be accurate and robust. Some options like the QHY174M-GPS camera [9] and systems such as ADVS and others [10, 11, 12] are capable to meet the needed accuracy but they are either not widely available or limited in the choice of image sensors and cameras for the amateur community. A recent article by Pavlov & Gault [13], showed that there is a way to accurately correct (better than ±15 ms in 99 % of the time) the PC system date/time using the *Meinberg NTP* software [14]. The method described by Pavlov & Gault requires an internet ADSL connection, has an initial time to achieve ±15 ms UTC synchronization within approximately 1-2 hours after a cold start, and exposes to similar times to recovery from a rare erroneous single shift during the synchronization [13].

Achieving accurate timing with a PC is challenging because it depends on many factors like the variability in the internal RTC clock, the tolerance (ppm) and variation with the temperature of CPU-clocking crystal oscillators, the presence of multiple motherboard CPUs in modern computers, high priority system interruptions by the operating system, different date/time management depending on the version of the operating systems among other factors [13]. A way to be sure that the *Windows* time will not be affected by multi-core and power management is to verify that the time is based on the crystal oscillator on the motherboard. As described in Pavlov & Gault, a method to verify these conditions is to check that the CPU used supports a feature called Invariant TSC and that this feature is supported by the *Windows* OS version used [13, 15]. The majority of *Windows 7* operating systems and above support Invariant TSC, but it is preferable to use *Windows 10* because of the additional improvements made to its kernel and task scheduler that directly affect the accuracy of the system date/time [13, 16].

In February 2020, the Shelyak TimeBox [17] in Figure 1 was released as an accurate and portable solution for UTC timing using digital video cameras in a *Windows* environment. The Shelyak TimeBox is designed to allow accurate timing of astronomical phenomena using digital video devices. It provides the base for several modular set-ups that can be used with a wide variety of astronomical hardware. The Shelyak TimeBox recovers the UTC time from GPS satellites and synchronizes the recordings using three different modes:

LED firing: This mode allows inserting the UTC time directly and optically in the video frame stream by firing a LED at each UTC-second. The accuracy of the rise of the LED firing was measured against the UTC-OP of the SYRTE at the *Observatoire de Paris* [18] to be delayed by +10 μs UTC.

Computer Synchronization: This mode allows the synchronization of a PC using a *Windows* operating system internal date/time with the UTC reference delivered and updated by the TimeBox device and proprietary software. Then computer synchronization mode allows the recorded frames to be accurately timestamped by the PC with the UTC-synchronized system date/time. The accuracy of the recordings made with the Shelyak TimeBox in computer mode was measured by the team of Pr. Sicardy. Their findings presented in Dr. Leiva's doctoral thesis showed that the accuracy of the recorded frames stayed below the resolution limit of the test defined at ± 20 ms UTC [19]. The accuracy of this method was also measured in-house by comparing the difference between timestamps of the recorded frames against the firing of a GPS 1PPS, and found to be approximately ± 5 ms UTC (>95%, 2 standard deviations) at the resolution limit of the sampling method ["Technical Datasheet and Controls", 20].

Trigger: In this mode the Shelyak TimeBox is able to trigger the camera driving the exposure by emitting a series of TTL logic square UTC-timed pulses through a BNC port at a frequency chosen between 0.1 and 24 Hz. In this mode, the Shelyak TimeBox is also able to synchronize the internal PC-clock to ease data reduction and produces a log containing the list of the pulses. The accuracy of this method was measured in-house by comparing the difference between the Shelyak TimeBox pulses against the firing of a GPS 1PPS using an oscilloscope, and found to be better than 1 ms UTC (data not shown).

Using the Shelyak TimeBox in both LED firing or Computer Synchronization requires a simple USB connection as the power needed is drawn from the USB port. On the other hand, Trigger mode needs additional power for firing the pulses sent into the I/O port of the camera. An additional 12 V power supply has to be connected into the dedicated Shelyak TimeBox 12 V DC-input when using the Trigger mode (Figure 1).

The goal of this article is to show the results of the independent testing of the Shelyak TimeBox using described methods [13, 21] that measure the accuracy of UTC timestamped recordings for both computer synchronization and trigger modes, to assess the accuracy of the timestamping when using different cameras and acquisition software, and to measure the accuracy of the PC date/time synchronization on long periods of time.

Shelyak TimeBox
Size : L 135mm x W 80 mm x H 40 mm
Weight : 220 g

Figure 1. The Shelyak TimeBox, a device designed for accurate UTC time recordings with digital video cameras.
A - Shelyak TimeBox face A.
B - Shelyak TimeBox face B, display the (left to right) USB-B port, GPS antenna SMA port, TTL trigger output port and 12 V DC-input for trigger mode.

Materials and Methods

Windows 10 and Windows 7 operating system time drift

A dual installation of *Microsoft Windows 10 Professional* and *Windows 7 Professional Service Pack 1* operating systems was done on a PC AMD FX-8350 4 GHz, 16Gb RAM system. The *TimeBox 1.8.2 XS* software version was installed in *Windows 10*, while the *TimeBox 1.8.2 Legacy* version in *Windows 7* ["Software and firmware", 17]. Each operating system was booted and a 15 minutes recording of the system's time drift compared to the Shelyak TimeBox timestamps done during the calibration routine for each operating system. The system date/time in *Windows 10* was read using the GetSystemTimePreciseAsFileTime function, and the system date/time in *Windows 7* was read using the GetSystemTime function. Linear fits for both recordings were calculated using the polynomial curve fitting "polyfit" (degree = 1) function in Matlab (R2020a).

Digital cameras with Shelyak TimeBox in Computer mode compared to SEXTA

A *Windows 10* 64-bits system (AMD FX-8350 4 GHz, USB2) was permanently synchronized using a Shelyak TimeBox in computer mode for at least 15 min using default synchronization parameters using the *TimeBox 1.8.2 XS* software version. Following, the screen of a SEXTA [21] device was recorded by three different digital cameras a Basler 640-100gm GigE Global shutter, a ZWO ASI183MM-Pro USB3 Rolling shutter and a Basler acA3088-57um USB3 Rolling shutter at 4, 10, 20 and 40 FPS for two min each. A constant time offset for each camera was determined and the frames timestamp corrected with the corresponding offset. All acquisitions were done using *Airylab's Genika Astro x64bits* (Release 2.13.5.8) as recording software [22] and the frames saved as a single SER file for each acquisition. Timestamps were recovered from the SER image header and compared to the SEXTA's optical timestamps using the provided *SEXTAreader* software [21]. In the case of rolling shutter cameras, the timestamps were corrected according to this formula: reading time of the line (tRow) x number of the line where we find the object to be dated (Row), the timestamp corresponds at the time when the camera records the first line.The reading time of the line (tRow) depends on the camera and can be obtained by:

$$tRow = (1/FPSmax)/TotalRow$$

FPSmax = Maximum frame rate (FPS)
TotalRow = Total number of lines read at that max FPS

Mean, STD and linear regression were calculated for each acquisition. Linear regressions were calculated using the polynomial curve fitting "polyfit" (degree = 1) function in Matlab (R2020a).

Acquisition software with Shelyak TimeBox in Computer mode compared to SEXTA

A *Windows 10* 64-bits system laptop (Lenovo ThinkPad Intel i5 Core i5-540M, 4GB DDR3 RAM, USB2.0) was permanently synchronized using a Shelyak TimeBox in computer mode for at least 15 minutes using default synchronization parameters using the *TimeBox 1.8.2 XS* software version. Following, the LED matrix screen of a SEXTA [21] device was recorded using a Basler 640-100gm GIgE camera with three different acquisition software: *Airylab Genik*a, *SharpCa*p and *PRISM* at 4, 10, 20 and 40 FPS frequencies for 2 min each. A constant latency time offset for each camera was determined and the frames timestamp corrected with the related offset. The acquisitions were done using *Airylab's Genika Astro x64bits* (Release 2.13.5.8) [22], *SharpCap* (3.2.6101.0) [23], and *PRISM* (v10) [24] and the frames saved as a single SER file for each acquisition. Timestamps were recovered from the SER image header and compared to the SEXTA's optical timestamps using the provided *SEXTAreader* software [21]. Mean delay and variance (standard deviation) for each frame recorded at all acquisition rates were calculated for each acquisition software and compared using a One-way ANOVA post-hoc test using Matlab's (R2020a) "anova1" and "multcompare" functions.

Shelyak TimeBox Trigger mode compared to SEXTA

A Shelyak TimeBox in trigger mode was used to produce UTC-synchronized TTL pulses used to trigger frame acquisitions on a Basler 640-100gm GigE digital camera recording the LED matrix screen of a SEXTA [21] device at 1, 2, 4, 8, 10, 15, 20 and 24 FPS for two min each. All acquisitions were done using the *TimeBox 1.8.2 XS* software version in a *Windows 10* 64-bits system laptop (Lenovo ThinkPad Intel i5 Core i5-540M, 4GB DDR3 RAM, USB2.0). *Airylab's Genika Astro x64* (Release 2.13.5.8) was used as recording software and the frames saved in a single SER file for each acquisition. Frames were set to be triggered using the built-in external trigger of the camera by checking the *Genika*'s "HW trigger" case as shown in the user manual page 25 [22]. A standard 12 V DC power plug was connected to the dedicated Shelyak TimeBox 12 V DC-input as described in the user manual page 14 [22]. The resulting SER video timestamps were re-synchronized with the acquisition TimeBox log using the *Airylab SER Toolbox* (v 2.0.1.0) included with *Genika*, as detailed in the Shelyak TimeBox user manual pages 20-21 [25]. The timestamps of the re-synchronized SER files were recovered from the frame header and compared to the SEXTA's optical timestamps using the provided *SEXTAreader* software [21]. The mean, STD and linear regression were calculated for each acquisition. Linear regressions were calculated using the polynomial curve fitting "polyfit" (degree = 1) function in Matlab (R2020a).

Shelyak TimeBox in computed mode compared to IOTA-VTI/ *OccuRec*

OccuRec [26] was used to survey the synchronization of the internal clock of a *Windows 10* 64-bits system (Toshiba Qosmio F750, Intel processor i7, 8Gb RAM and Samsung EVO 850 SSD hard drive) to the Coordinated Universal Time (UTC) for 4 h, 6 h, and 24 h at 24 timestamps/second as described in Pavlov & Gault [13]. The computer internal clock was permanently synchronized using a Shelyak TimeBox in computer mode with default synchronization parameters; different "Time correction" modes were tested: Slow, Medium and Fast, the synchronization was done using the *TimeBox 1.8.2 XS* software version. *OccuRec* recorded the system time using

the *Windows 10* GetSystemTimePreciseAsFileTime function against a time reference provided by the IOTA-VTI obtained by automatically reading the OCR timestamp for every single frame during the recording (40 ms, PAL). Matlab (R2020a) was used to calculate a one-minute (1440 timestamps window) moving mean of the delay (ms) between the Shelyak TimeBox and the IOTA-VTI obtained by using the "movmean" function, and linear regressions by using the polynomial curve fitting "polyfit" (degree = 1) function. The frequency distribution of the delays between the Shelyak TimeBox and the IOTA-VTI were represented in a histogram. The statistical measures of the mean of the delay (ms), STD, maximum, minimum and number of measures (n) are shown for each recording.

Results

In order to determine the more accurate method for reading the system date/time in a *Windows* PC, a dual installation of *Microsoft Windows 10 Professional* and *Windows 7 Professional Service Pack 1* operating systems was done on a single PC (see chapter *Materials and Methods*). A dual installation allowed to prevent bias in the recordings due to hardware variability [13]. Each operating system was booted individually, two installations of the Shelyak TimeBox software were done in each operating system: *TimeBox 1.8.2 XS* version in *Windows 10* and the *TimeBox 1.8.2 Legacy* version in *Windows 7*. The *TimeBox XS* version is compatible with *MS Windows 8* system and up and uses the GetSystemTimeAsPreciseAsFileTime function to read the system date/time, while the *TimeBox Legacy* version is compatible with *MS Windows XP* systems and above and uses the GetSystemTime function to read the system date/time. After installing the corresponding *TimeBox*

software, the same Shelyak TimeBox device was connected to the computer USB2 and the antenna was placed in an open-sky location to allow the internal GPS of the Shelyak TimeBox to be fixed. After fixation one mandatory calibration routine was done for each operating system. A calibration file was produced after each calibration routine; this file contains 15 min recordings of the system's date/time drift compared to the Shelyak TimeBox UTC timestamps.

As shown in Figure 2, both functions GetSystemTimePreciseAsFileTime and GetSystemTime measure a similar system time drift as expected when measuring on the same computer. GetSystemTimePreciseAsFileTime measured a slope of 2.02 ms/min while GetSystemTime measures a slope of 1.77 ms/min (Figure 2A). On the other hand, we observed that the variance of the date/time measures was significantly increased when using the *Windows 7* GetSystemTime function compared to the *Windows 10* GetSystemTimePreciseAsFileTime function (Figure 2B). The subtraction of the slope during the time drifts was used to measure the variances ± 2.4 and ± 10 ms UTC (>95%, 2 standard deviations) for GetSystemTimePreciseAsFileTime and GetSystemTime respectively (Figure 2B). The increase in the variance was also reflected on the linear correlation coefficient measured at r = 0.51 and r=0.96 for GetSystemTime compared to GetSystemTime-PreciseAsFileTime respectively (Figure 2A). These results show that the *Windows 10* GetSystemTimePreciseAsFileTime is better suited to read the system date/time compared to the *Windows 7* GetSystemTime function. Recent developments on the system date/time reading were done when releasing *Windows 8* to provide microsecond resolution of the timestamps when using the GetSystemTimePreciseAsFileTime function [13, 27, 28]. For this
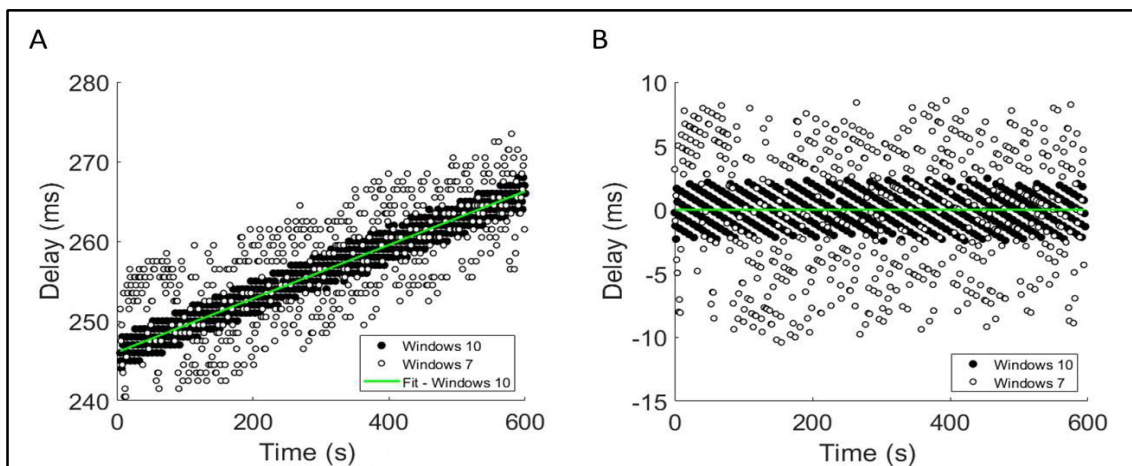

Figure 2A, B. Windows 10 GetSystemTimePreciseAsFileTime function improves system's date/time reading.
15 minutes recordings of the system's date/time drift compared to the Shelyak TimeBox timestamps. The system's date/time drift was read either in Windows 10's using GetSystemTimePreciseAsFileTime function (● filled circles) or in Windows 7 using GetSystemTime function (○ empty circles).
A) Linear fits for both measurements were calculated for Windows 10 GetSystemTimePreciseAsFileTime with a slope = 2.02 ms/min and a r = 0.96 represented in green, and Windows 7 GetSystemTime with a slope = 1.77 ms/min and a r = 0.51.
B) Subtraction of the slopes during the system date/time drifts were used to measure the standard deviations ±1.2 and ±5.0 ms UTC when using GetSystemTimePreciseAsFileTime and GetSystemTime function respectively.
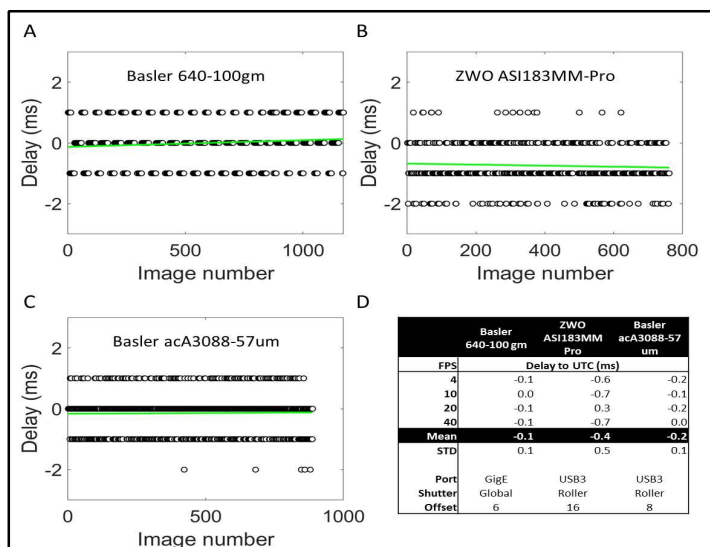
Figure 3A-D. Shelyak TimeBox in Computer mode allows the accurate timestamping of recordings for both global/rolling shutter digital cameras.
Different digital cameras were used to record a SEXTA device for 2 minutes at different acquisition frequencies; the system's date/time was synchronized using a Shelyak TimeBox in Computer mode and Airylab's Genika as acquisition software. Representative result of the Delay (ms) between the frames timestamps and the SEXTA optical timestamps for the duration of the recording (10 FPS) are shown:
A) Basler 640-100gm GigE Global shutter camera
B) ZWO ASI183MM-Pro USB Rolling shutter camera
C) Basler acA3088-57um USB Rolling shutter camera.
The results of the measures at different acquisition rates for all three cameras are shown in D, where the mean Delay (ms) for each acquisition is corrected for the constant time offset (ms) of the recording.

	Basler 640-100 gm	ZWO ASI183MM Pro	Basler acA3088-57 um
FPS	Delay to UTC (ms)		
4	-0.1	-0.6	-0.2
10	0.0	-0.7	-0.1
20	-0.1	0.3	-0.2
40	-0.1	-0.7	0.0
Mean	-0.1	-0.4	-0.2
STD	0.1	0.5	0.1
Port	GigE	USB3	USB3
Shutter	Global	Roller	Roller
Offset	6	16	8

reason, all the following tests were performed on *Windows 10* systems using the *TimeBox 1.8.2 XS* software version that uses the GetSystemTimePreciseAsFileTime function to read the system date/time.

In order to measure the UTC timestamp accuracy of frames recorded by a PC permanently synchronized using a Shelyak TimeBox in computer mode, the screen of a SEXTA [21] device was recorded using three global or rolling shutter cameras: Basler 640-100 gm, ZWO ASI183MM-Pro and Basler acA3088-57um. The recordings were done at different acquisition frequencies for 2 min using *Airylab Genika* as acquisition software as described in *Materials and Methods*. The delay between each frame timestamp was subtracted from the SEXTA optical timestamp read by the provided *SEXTAreader* software; representative results for an acquisition frequency of 10 FPS are shown in Figure 3A, 3B and 3C for each camera.

The results of the measurements at different acquisition rates for all three cameras are shown in Figure 3D. The analysis of the mean delay for each camera and acquisition frequencies show that there is a constant time offset for all acquisition frequencies for each camera (Figure 3D, Offset). A constant time offset was observed when recording with digital systems [13], to measure it the Shelyak TimeBox possesses a built-in LED and a procedure that allows measuring this offset described on page 17 of the user manual [25]. The constant time offset for the Basler 640-100 gm, ZWO ASI183MM-Pro and Basler acA3088-57um were measured at +6, +16 and +8 ms respectively. The constant time offsets were used to correct the frames timestamps for each camera at any given acquisition frequency. The results in figure 3D show that the corrected mean of the UTC-timestamps of the recordings done with a Basler 640-100 gm, a ZWO ASI183MM-Pro and a Basler acA3088-57um cameras measured at -0.1, -0.4 and 0.2 ms with standard deviations of ± 0.1, ± 0.5 and ± 0.1 respectively. It is

important to note that the recording made with the rolling shutter cameras needs to be corrected as described in *Materials and Methods*; indeed the rolling shutter mode induces a drift of the exposure start and end through the array [8]. These results show that the accuracy of the UTC timestamps recorded with these digital systems permanently synchronized with a Shelyak TimeBox in computer mode is better than 1 ms with mean standard deviations of less than ± 0.5 ms. It is important to remember that the configuration of the SEXTA used during these recordings offers a temporal resolution down to 2 ms referred to UTC [21].

To evaluate the impact of using different acquisition software on the accuracy of UTC timestamps, a laptop PC was permanently synchronized by a Shelyak TimeBox in computer mode. The screen of a SEXTA device was recorded using a Basler 640-100 gm camera for 2 min at different acquisition frequencies. Three different acquisition software were used: *Airylab Genika*, *SharpCap* and *PRISM* as described in *Materials and Methods*. Figures 4A-4D show the delay between each frame timestamp subtracted from the SEXTA optical timestamp at each acquisition frequency. As shown in Figure 4A, the accuracy of the UTC timestamping done with *Airylab's Genika* is better than 1 ms (0.1 ms) UTC with a standard deviation of ± 0.7 ms and a constant time offset of +6 ms. These measures are similar to those presented in Figure 3, the variation of the standard deviation is possibly due to the use of different PCs for each measure (see *Materials and Methods*). As shown in Figures 4B and 4D, the variance of the UTC timestamps when using *SharpCap* as acquisition software was comparable to that observed when using *Airylab Genika* (standard deviation, Figures 4A, 4B and 4D). On the other hand, the analysis of the mean UTC delay when using *SharpCap* showed that the timestamp of the frames is recorded at the end of the exposure. When using *SharpCap* as acquisition software, the resulting timestamps add the exposure time of the frame to the constant time offset measured at +5 ms (Figures 4B and 4D).

In contrast, the variance of the UTC timestamps when using *PRISM* was greatly increased compared to the variance observed when using either *Airylab Genika* or *SharpCap* (Figures 4C, 4D and 4E). Indeed, the standard deviation of the UTC timestamp delay was more than x140 (STD = ± 139 ms) times higher than those measured with Airylab *Genika* and *SharpCap* (STD = ± 0.7 and ± 1 ms, respectively). The analysis of the mean UTC delay when using *PRISM* showed that the timestamp of the frames is done at the end of the exposure, but in contrast to either *Airylab Genika* or *SharpCap* the time offset was not constant for each acquisition frequency. For this reason, a mean time offset of +37 ms was calculated from all different acquisition frequencies and used to correct the mean UTC time delays (Offset, Figure 4D). Moreover, the mean UTC delay was x77 times higher when using *PRISM* (mean delay = 7.7 ms) compared to those obtained with either *Ariylab Genika* or *SharpCap* (mean delay = 0.1 and 0.2 ms respectively). The difference in the mean and variance of the timestamps obtained with *PRISM* was compared to those obtained when using *Airylab Genika* and *SharpCap* and found to be statistically different (Figure 4E and *Materials and Methods*).

In order to measure the UTC timestamp accuracy of frames recorded when using a camera triggered by a Shelyak TimeBox, a Basler 640-100gm GigE digital camera was used to record the screen of a SEXTA device at 1, 2, 4, 8, 10, 15, 20 and 24 FPS for two min. The recordings were done using *Airylab Genika* as acquisition software, the frames were set to be triggered using the built-in external trigger of the camera as described in *Materials and Methods*. The results of the measures at different acquisition rates are shown in Figure 5. The delay between each frame timestamp was subtracted from the SEXTA optical timestamp; representative results for an acquisition frequency of 8 FPS are shown in Figure 5A and 5B. In Figure 5B at 8 FPS, we observed that the mean timestamp delay for all individual UTC-synchronized TTLs within a second was constant and measured to be better than 1 ms (0.9 ms) with a standard deviation of ± 0.6 ms (Figures 5B and 5C). No constant time offset was measured at any acquisition frequency as expected by the +16 μs delay between the TTL and the start of the exposure announced by the manufacturer [28]. Figure 5C shows the delay between each frame timestamp subtracted from the SEXTA optical timestamp at each acquistion frequency. As shown
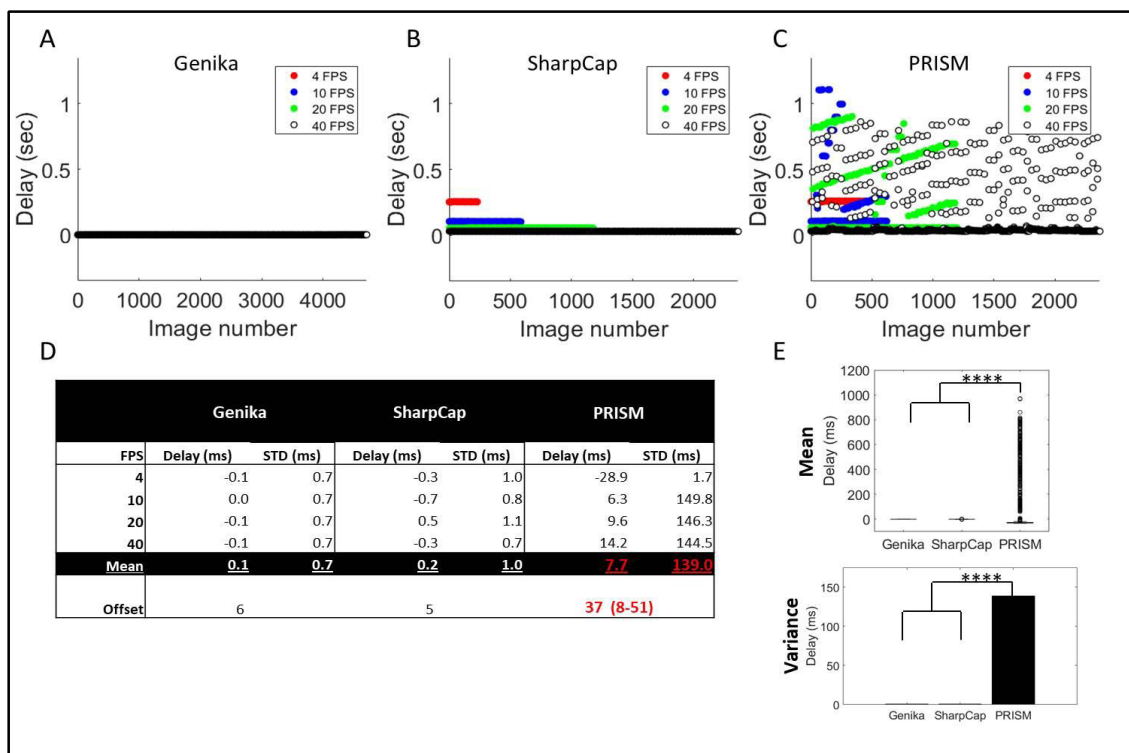

	Genika		SharpCap		PRISM	
FPS	**Delay (ms)**	**STD (ms)**	**Delay (ms)**	**STD (ms)**	**Delay (ms)**	**STD (ms)**
4	-0.1	0.7	-0.3	1.0	-28.9	1.7
10	0.0	0.7	-0.7	0.8	6.3	149.8
20	-0.1	0.7	0.5	1.1	9.6	146.3
40	-0.1	0.7	-0.3	0.7	14.2	144.5
Mean	**0.1**	**0.7**	**0.2**	**1.0**	**7.7**	**139.0**
Offset	6		5		37 (8-51)	

Figure 4A-E. The acquisition software is essential to allow the accurate timestamping of recordings.
*Different acquisition software were used to record a SEXTA device for 2 minutes at different frequencies with a Basler 640-100gm camera; the system's date/time was corrected using a Shelyak TimeBox in Computer mode. The results of the Delay (ms) between the frames timestamps and the SEXTA optical timestamps at different acquisition frequencies are displayed (4FPS filled red circles, 10 FPS filled blue circles, 20 FPS filled green circles and, 40 FPS empty black circles) for A - Airylab Genika, B - SharpCap and C - PRISM. The results of the measures at different acquisition rates are shown in D, where the mean Delay (ms) for each acquisition was corrected for the constant time offset (milliseconds) of the recording and for the duration of the exposure in the case of SharpCap and PRISM. The mean delay and variance (standard deviation) for each frame recorded at all acquisition rates were calculated for each acquisition software and compared using a One-way ANOVA post-hoc test (p = 1.0698e-09 ****) and are shown in E.*
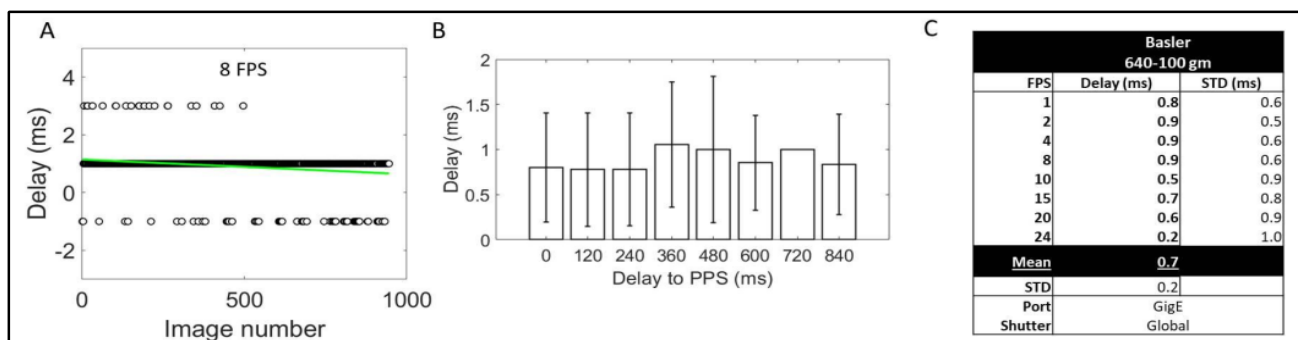
Figure 5A-C. Shelyak TimeBox in Trigger mode allows accurate millisecond timestamping of recordings with I/O triggered digital cameras.
A I/O triggered Basler 640-100gm digital camera was used to record a SEXTA device for 2 minutes at different acquisition frequencies; the recording frames were triggered using a Shelyak TimeBox in Trigger mode at different frequencies. The recorded frames were captured using Airylab Genika as acquisition software.
A) Representative result of the Delay (ms) between the triggered frames timestamps and the SEXTA optical timestamps for the duration of the recording (8 FPS)
B) Delay of the individual triggered frames for each second during a representative recording (8 FPS).
The results of the measures at different acquisition rates are shown in C, where the mean Delay (ms) for each acquisition was measured.

in Figure 5C, the mean and standard variation of the UTC timestamping in trigger mode for all the recordings is less than 1 ms (0.7 ms) UTC and ± 0.2 ms respectively. These results show that the accuracy of the UTC timestamps recorded using the Shelyak TimeBox trigger mode is constant across the acquisition frequencies and to 1 ms UTC. It is important to remember that the configuration of the SEXTA used during these recordings offers a temporal resolution down to ± 2 ms referred to UTC [21].

During the last series of experiences, we wanted to measure the accuracy of the UTC synchronization of a PC permanently syn

chronized using a Shelyak TimeBox in computer mode for long periods of time. To achieve this, the *OccuRec* software [26] was installed and ran on a PC as described in Pavlov & Gault [13, 26]. *OccuRec* was used to record around 345.6 thousands (Figures 6A, 6D and 6G), 1.7 million (Figures 6B, 6E and 6H) and 518.4 thousands (Figures 6C, 6F and 6I) timestamps comparing the system date/time synchronized with a Shelyak TimeBox in computer mode compared to the IOTA-VTI for 4, 20 and 6 h respectively as described in *Materials and Methods*. As shown in Figures 6A and 6D when using the "Time correction" parameter "Slow", the PC date/time synchronization was regular over the 4 h with a mean
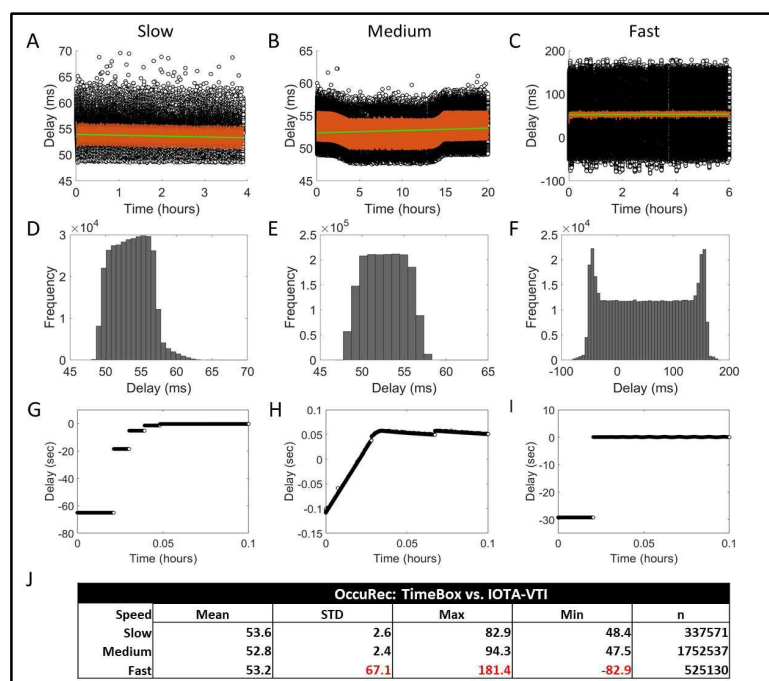

Figure 6A-J. Shelyak TimeBox in Computer mode allows stable and accurate timestamping of the system time/date over long periods of time.
Around 345.6 thousands (A and D), 1.7 million (B and E) and 518.4 thousands (C and F) Delay (ms) comparing the system date/time synchronized with a Shelyak TimeBox in Computer mode compared to the IOTA-VTI OCR timestamp were recorded for 4, 20 and 6 h (24 timestamps/second) using OccuRec.
Figures A and D correspond to the default Shelyak TimeBox time correction setting "Slow", Figures B and E corresponds to "Medium" and Figures C and F to "Fast".
The orange plot on Figures A, B and C represents a one-minute moving average of the Delay (ms), while the linear fit for each measure is shown in green. Histograms representing the Delay (ms) for each correction setting (Slow, Medium and Fast) are displayed in Figures D, E and F.
Figures G, H and I correspond to a magnification of the first 6 minutes preceding the recordings shown on Figures A, B and C respectively.
The results of the linear fits and statistical measures for each Shelyak TimeBox time correction setting are shown in J.

delay of 53.6 ms and s standard deviation of ± 2.6 ms (Figure 6J). Similarly, on Figures 6B and 6E when using the "Time correction" parameter "Medium", the PC date/time synchronization was regular over the 20 hours with a mean delay of 52.8 ms and a standard deviation of ± 2.4 ms (Figure 6J). On the other hand, PC date/time synchronization was irregular when using the "Time correction" setting "Fast" on this system. The PC date/time synchronization using the "Time correction: Fast" showed high variations around the mean delay measured at 53.24 ms, and reflected in the dispersion of the individual measures around ± 180 ms, with a standard deviation of ± 67.1 ms as shown in the plot containing the individual measures (Figure 6C), the histogram representing frequency of the measures (Figure 6F) and the standard deviation around the mean (Figure 6J). It is important to note that these high variations in the PC system date/time synchronization were measured and accounted for in the Shelyak TimeBox log files produced during the synchronization routine. As described in Pavlov & Gault [Acquisition Delay, 13], the constant time delay of around 53 ms UTC is due to the time added by the frame grabber to digitise the recording coming from the IOTAVTI. These results show that it is important to measure the optimal correction rate of the synchronization for each system to avoid overcorrection and instability on the synchronization of the PC date/time when using the Shelyak TimeBox in computer mode.

Figure 6G, 6H and 6I correspond to a magnification of the first 6 min preceding the recordings shown on Figure 6A "Slow", 6B "Medium" and 6C "Fast" respectively. The initial delay in the PC date/time was 1 min, 100 ms and 30 s for the three recordings respectively. We observed that in these three different settings, the Shelyak TimeBox was able to quickly and accurately correct the PC date/time under 3 min after the start of the synchronization (Figures 6G, 6H and 6I). These initial delays were accounted for by the Shelyak TimeBox from the first second of the synchronization and recorded in the log files produced during the recordings. As recommended in the Shelyak TimeBox user manual, accurate reading of the PC time in *Windows* environments needs to filter out random variations, extract a stable and accurate time base and correctly correct the system's date/time [25]. For this reason, it is recommended to leave at least 15 min after the start of the PC date/time synchronization before recording astronomical phenomena, in order to obtain an accurate UTC and stable PC date/time. The results of the statistical measures on all three conditions are shown in Figure 6J.

Discussion

As discussed in the introduction, the goal of this article was to measure the accuracy of the system date/time reading using different *Windows* functions, to independently test the Shelyak TimeBox using described methods [13, 21] for both computer and trigger modes, to assess the accuracy of the timestamping when using different cameras and acquisition software, and to measure the accuracy of the PC date/time synchronization at long periods of time.

We confirmed that the *Windows 10* GetSystemTimePrecise-AsFileTime function outperforms the former *Windows 7* and earlier GetSystemTime function for accurately reading the system date/time (Figure 2). As noted in Pavlov & Gault [13, 15], *Windows 10* added additional improvements to its kernel and task scheduler that directly increases the accuracy of the system date/time. Also the GetSystemTimePreciseAsFileTime function resolution was increased up to the microsecond when compared to the millisecond only resolution of the GetSystemTime when reading the system date/time [27, 28]. For these reasons we recommend using *Windows 10* and reading the system date/time with the GetSystemTimePreciseAsFileTime function when recording astronomical occultations and other phenomena that need accurate UTC timestamping. The measures performed in this article were done in three different *Windows 10* PCs, probably with different *Windows 10* updated versions without altering the results. A number of users around the world routinely use the Shelyak TimeBox with their *Windows 10* PCs. So far, no complaints or problems due to *Windows 10* updates were raised for using the Shelyak TimeBox in different systems.

Moreover, the results shown in Figure 3 revealed that it is possible to accurately timestamp astronomical occultations up to 1-2 ms UTC when recorded using a PC permanently synchronized using a Shelyak TimeBox in computer mode. The results were similar when using Global/Rolling shutter and GigE/USB3 cameras; it is important to note that the recording made with a Rolling Shutter camera needs to be corrected for the line where the object appears as the timestamp corresponds to the time when the camera records the first line (see *Materials and Methods*). It would be interesting to consider adding an automatic correction of the timestamp for each object when recordings are done with Rolling Shutter cameras either in the acquisition software (*Airylab Genika* or *SharpCap*) or in the reduction software like *Tangra* [30]. Also, the analysis of the mean delay for each camera and acquisition frequencies showed that there is a constant time offset for all acquisition frequencies for each recording camera (Figure 3D, Offset). This is one important element to consider to allow an accurate UTC timestamping when using digital systems; the Shelyak TimeBox possesses a built-in LED and a procedure that allows to measure this offset and a procedure is described on page 17 of the Shelyak TimeBox user manual [25].

The accuracy of the UTC timestamps obtained using the Shelyak TimeBox in computer mode was assessed in the past using different methods than those presented in this article [19, 20]. One of these measures consisted in recording a firing 1PPS LED and comparing the digital timestamps of the frames to the 1PPS LED optical timestamps as described in the Shelyak TimeBox user manual page 17 [25]. These measures were done using a Basler 1300-60gm GigE Global Shutter and a Raptor Photonics EMCCD Kite Global Shutter recording cameras with similar results that those presented in this article [20]. No apparent restrictions were observed for using digital cameras currently available for astronomical applications. Nonetheless, no measure was done to

assess the accuracy of the timestamping with neither DSLR nor mechanical shutter equipped cameras as we considered the evaluation of these devices out of the scope of this article.

As described in Barry et al. [21] camera control and acquisition software produces timestamps with widely varying fidelities to UTC. This was confirmed in Figure 4, where the recordings done with *PRISM* showed an extremely high timestamp variance, a non-constant time offset resulting in an inaccurate recording unsuitable for astronomical occultations. On the other hand, *Airylab Genik*a and *SharpCap* were able to record accurate UTC timestamps with low variance and a constant time offset. It is very important to note that *SharpCap* timestamps were done at the end of the exposure, adding this exposure time to the timestamp. This *SharpCap* characteristic was not described in the software documentation available at the date of the recordings, it would be preferable to explicitly describe this behaviour or to add a functionality allowing the date the timestamps at the start of the exposure by automatically subtracting the exposure time for each frame during the recording. As pointed out in this article, a vital factor in the accuracy of the timestamping is the choice of the recording software. Approved and tested recording software are able to accurately capture and timestamp frames, a variety of file formats can be used for the recordings if they are non-compressed and accurately timestamped.

Also, the UTC timestamp accuracy of frames recorded when using a camera triggered by a Shelyak TimeBox was measured and shown in Figure 5. These results showed that the accuracy of the UTC timestamps recorded using the Shelyak TimeBox trigger mode is better than 1 ms UTC and without any constant time offset. It is important to remember that the configuration of the SEXTA used during these recordings offers a temporal resolution down to ± 2 ms referred to UTC [21], so it will be interesting to test this mode using a higher resolution optical system like the EXposure Time Analyzer (EXTA) [30] or comparing the delay between the UTC-synchronized TTLs against TTL pulses produced by the UTC OP SYRTE atomic clock [18].

Furthermore, the results of the recordings shown in Figure 6 revealed that the Shelyak TimeBox was able to quickly and accurately correct the PC date/time under three minutes after the start of the synchronization (Figures 6G, 6H and 6I) and for long periods of time that exceed the 24-hours duration of the longest test. It is important to note that between the different parameters that played a role in the PC date/time for longer periods of time, the "time correction" setting showed to be important for having an optimal correction rate, avoid overcorrection and instability on the synchronization of the PC date/time when using the Shelyak TimeBox in computer mode.

A very broad range of USB and serial port GPS devices are available in the market. From simple navigation aids with no claim by the manufacturer of any time-keeping ability, to specialized devices where the manufacturer claims some degree of time accuracy achieved by various means. Apart from the Shelyak TimeBox no other device was tested in this article, authors cannot comment further on the accuracy of the timestamps obtained using these devices. The authors encourage the community of astronomers to test the timestamping accuracy of pertinent USB and serial port GPS devices in the future.

The results of the tests and recording presented in this article showed that the Shelyak TimeBox was able to allow quick and accurate UTC timestamped recordings using digital cameras. Using the Shelyak TimeBox in computer mode was measured to be accurate up to 1-2 ms UTC when using both GigE and USB3 cameras. It is important to note that in order to assure accuracy using the Shelyak TimeBox in computer mode, it is vital to choose an approved and tested software like *Airylab Genika* and to measure and correct the constant time offset in each PC +camera system. An undergoing initiative by the IOTA timing commission works on testing and classing the most currently used acquisition software in astronomy on their ability to ensure accurate UTC timestamps during the recordings with digital cameras. Also, the results of the tests of the Shelyak TimeBox in trigger mode showed that its accuracy was beneath 1 ms UTC and without any constant

Shelyak Timbox Mode	Camera	Acquisition Software	Accuracy and STD	Notes
Computer	Basler 640-100gm, GigE and Global shutter	Airylab Genika	-0.1 ± 0.1 ms	Constant time offset +6 ms
Computer	ZWO ASI183MM-Pro, USB3 and Rolling shutter	Airylab Genika	-0.4 ± 0.5 ms	Constant time offset +16 ms. Rolling shutter correction*1
Computer	Basler acA3088-57um, USB3 and Rolling shutter	Airylab Genika	0.2 ± 0.1 ms	Constant time offset +8 ms. Rolling shutter correction*1
Trigger	Basler 640-100gm, GigE and Global shutter	Airylab Genika	0.9 ± 0.6 ms	No constant time offset
Computer	Basler 640-100gm, GigE and Global shutter	SharpCap	0.2 ± 1.0 ms	Constant time offset +5 ms. Timestamp at the end of the exposure*2
Computer	Basler 640-100gm, GigE and Global shutter	PRISM	7.7 ± 139.0 ms	Variant time offset. Timestamp at the end of the exposure*2.Not suited for timestamping
Computer	-	OccuRec	53 ± 2 ms	Frame grabber offset of 53 ms*3

Figure 7. Summary table of the results.
A table with the summary of the results is presented with the Shelyak TimeBox mode used (computer or trigger), the camera, acquisition software (Airylab Genika, SharpCap or PRISM), the overall accuracy and standard deviation of the recordings and notes.
*1 Rolling shutter cameras induce a drift of the exposure start/end through the array. A correction was applied (Materials and Methods).
*2 The frames were timestamped at the end of the exposure.
*3 Constant time delay 53 ms due to the time to digitise the recording coming from the IOTA-VTI with the frame grabber [13].

time offset. The accuracy in trigger mode could allow to increase the resolution of asteroids shape when recording occultations of brighter targets with large telescopes and sensitive cameras at higher acquisition frequency than those currently used.

In Figure 7, a table with the summary of the results is presented with the Shelyak TimeBox mode used (computer or trigger), the camera, acquisition software (*Airylab Genika*, *SharpCap* or *PRISM*) and overall accuracy. The methodology used in this article for assessing the accuracy of the Shelyak TimeBox and the timestamping of different acquisition software/cameras can be used to test additional configurations used for occultations and other astronomical phenomena requiring precise UTC timestamping. It is interesting to note that being able to separate the UTC timestamping device from the recording camera will allow the use of last-generation, sensitive and low noise CCD, EMCCD and CMOS image sensors to be used for occultations. Also, the multimode design of the Shelyak TimeBox will allow amateur astronomers to use their current recording system without investing nor modifying their current hardware acquisition setup in most of the cases.

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