Analysis of synchronism and response velocity in instrumental assemblies for the observation of stellar occultations

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Abstract. Currently the stellar occultation technique is one of the most effective methods for observing minor bodies of the Solar System. Due to the collaborative nature of these observations, precise synchronization and short response times are necessary in instrumental assemblies. This paper presents the development of a methodology that allows for the evaluation of the temporal performance of the detectors used in the observation of stellar occultations. The software “TimesCCam” was developed, which, when being photographed by astronomical cameras, graphically represents the parameters of exposure time, dead time, and jitter referenced to UTC. The process of alignment and focus is obtained, thanks to a structure built with movement in the three axes. The methodology was applied in the evaluation of STF-8300M, ST-2000XM and QHY174M-GPS cameras, using different driver software, synchronization methods, and exposure times. In real exposure times, insignificant variations were identified. Dependency was found between the dead times and the configurations used for the CCD cameras, and it was determined that the dead time and its instability in the ST-2000XM camera prevent its use for the observation of stellar occultations. The results show that the STF-8300M camera is convenient for the observation of asteroid occultations, while the QHY174M-GPS camera, given its dead time and synchronization, is suitable for the observation of occultations by trans-Neptunian objects.

1. Introduction
Today, the study of asteroids and comets is highly relevant, since these objects play a fundamental role in the evolutionary models of the Solar System [1]. Nevertheless, for most discovered asteroids only their trajectory is known because of their distance and/or small sizes. The stellar occultations technique allows to determine physical and morphological information of the occulting minor body [2], thereby establishing itself as an alternative approach to the study of these objects [3]. This technique consists in recording the extinction of light when a minor body comes in front of a background star from our point of view from Earth [4].

Stellar occultations observations from different locations on the projected shadow increase the likelihood that the event will be registered. Decisive calculations of the occulting body can be derived due to these observations [5]. This is why the stellar occultations are characterized as a highly collaborative work [6], [7]. The aforementioned information leads to one of the
critical factors for deployed stations in observation campaigns: knowing the exact start time and end time of each exposure. These measurements are key for the treatment of the data obtained during campaigns, as all the observations must be referenced to common time base [8]. At present, most of the instrumental equipment obtain a measure of time through Global Positioning Systems (GPS), referencing a UTC time. Another possibility to reference a common time consists in the use of Network Time Protocol (NTP), synchronizing the computer clock with internet timeservers [9].

The velocity of the occulting minor body is in the order of the orbital velocity of the Earth (∼30 km/s). This implies that in addition to the high spatial location these events have durations in the order of seconds [5]. Like so, the technique of stellar occultations involves optic systems and detectors whose instrumental requirements are imposed by their high spatial and temporal locations. Thus, a high temporal resolution in the measurements, in terms of a high cadence, results in an adequate spatial resolution of the studied body [8]. The most used photometric instrument today for occultations observations in the visible spectrum is the CCD camera (Charged-coupled device) [10] given its high quantum efficiency. However, the use of cameras with CMOS (Complementary metal-oxide-semiconductor) sensors is growing due to their high cadences [11], despite initial problems of high read noise and low quantum efficiency [12]. Taking this into account, the data acquisition system must be capable of working in millisecond time intervals, which provides a representative light curve sample. That is, short exposure times are required for each frame, added to a minimum dead time between exposures. The camera shutter, too, must be taken into account, since this generates latency between the start trigger and the real capture of photons [5]. With regard to the software used for camera control, this influences the capture-time stability [9]. The computational requirements depend mainly on the camera, where fast processors, high velocity hard disks, and high amounts of memory are relevant [10], [13]. So, both hardware and software influence the characteristics of measuring time, since they imply delays related to clock reading [14].

The collection and later analysis of data obtained by each station require to determine the measurement accuracy in the start and end time of each capture [10]. This situation necessitates finding the real exposure time, real read time, and jitter. Initially, exposure time measurement methods used were based on the recording of the lines in a cathode rays television screen. Meanwhile [15] perform the measurement of the synchronization accuracy using an intermittent light emitting diode (LED), installed in the optical path of the telescope and controlled by GPS. An independent and controlled measurement of the capture characteristics can be obtained by this method. Conversely, [9], an Arduino-based system can obtain the real exposure time, dead time between frames, jitter, and the timing accuracy in a more precise way. The previous system consists in a panel with 500 LEDs which are synchronized with a GPS receiver, in which each LED turns on successively in specific intervals along the array. In this way, when pointing the camera to the working system, the images collected present an optical timestamp that indicates the passage of time, and subsequently can be contrasted with the timestamp of the detector.

The previous system is not easily reproduced due to the amount of electronic elements that must be paired as well as the high cost of the Arduino boards, GPS receivers, and other components. Subsequently, this type of system is contrary to the approach of developed equipment for occultations, where the systems are required to be replicated. Further, it does not present information about the procedure to get the panel in focus. This situation is aggravated by the fact that a considerable percentage of amateur astronomers participate in stellar occultations campaigns [14], which require simple and easily reproducible measurement methods. The present work developed an easily replicable method that allows both professional and amateur astronomers to determine the temporal performance of the instrumental assemblies for the observation of stellar occultations. This method was developed to measure the exposure time, dead time, and jitter, as well as determine the accuracy of the timestamp. The said
measurements were made in the STF-8300M, ST-2000XM and QHY174M-GPS cameras which has the Astronomical Observatory of the Technological University of Pereira.

2. Methodology
In the present paper, three essential characteristics of instrumental systems for the observation of stellar occultations were measured:

- **Exposure time:** Given an exposure time programmed by the controller software and given the chosen configuration, the actual times in which the sensor remained active were determined. The stability of this exposure time was evaluated with the sequence of captured images, visualizing their real values with respect to the capture number.

- **Dead time:** The cameras take a while to read the charge acquired by each of the pixels. The dead time behavior of each camera was established. As for the exposure time, the stability of this read time was found with respect to the capture sequence.

- **Synchronization:** The accuracy of the NTP and GPS synchronization methods was evaluated with the jitter determination. To determine this, the start time and the final time of each capture of the optical stamp are decoded and contrasted with the time embedded in the header of the image. This difference is determined by calculating its average, maximum value, minimum value and standard deviation. Finally, the difference found in each of the photographs is displayed according to the order in which they were taken.

3. Measurement protocol

![Figure 1. Illustrative scheme of the assembly: 1. Astronomy camera. 2. SLR camera lens. 3. Structure. 4. Cell phone.](image1)

![Figure 2. Model of the main platform.](image2)

The diagram presented in Figure 1 illustrates the assembly developed for the evaluation of the temporal performance of detectors used in the observation of stellar occultations. To determine the values of the parameters described above, the following protocol is applied: The astronomy camera target of the measurements must be located on the secondary platform of the base structure. On the main platform the SLR camera lens is located and will be used to focus the image of the display on the camera. The cell phone or tablet with the installed application must be located at a specific distance from the camera-lens set. Optical alignment of the camera and the lens is obtained through the developed assembly as well as the capability to move the
camera-lens set to focus the screen of the mobile device. Once a focused image of the screen is achieved, the application is executed. After synchronization takes place, the capture of images begins. The capture process is done using different configurations, varying the camera controller software, the synchronization method, and the exposure time for each camera. By comparing the optical stamp provided by the application, and the own stamp of the system used, it is possible to determine and analyze the exposure time, dead time, and jitter parameters.

3.1. Alignment and focus
To obtain a focused image of the screen, the sensor of the camera and the lens must be correctly aligned, so that an accurate projection of the image on the sensor is obtained. This alignment is affected by the differences between the geometries of the astronomy cameras and the location of the sensor. Taking this into account, a structure with movement in the X, Y and Z axes was designed and built for the optical alignment and the focus of the screen. After placing the lens and camera on the main and secondary platform respectively, the camera must be brought as close to the lens as possible. Figure 2 shows the model of the main platform. From the movement in X and Z of the platform that holds the lens, alignment is obtained between the optical axis of the lens and the sensor of the camera. The minimum focusing distance of the camera-lens set depends on the characteristics of the lens. This way, thanks to the Y movement of the structure, it is possible to move the camera-lens set until reaching said distance using the mobile device as a reference. In case the focus distance is too high and a focused image of the screen cannot be obtained, reverse the orientation of the lens. That decreases the minimum focusing distance and involves bringing the camera-lens set closer to the screen. Conversely, by using lenses in which it is possible to modify the focal relation, one can explore with different projected image sizes in a simple manner.

3.2. Mobile application
The observation of stellar occultations is a highly collaborative work that involves the participation of all kinds of people dedicated to astronomy. Because of this, the systems used in this field must be simple to use and easily replicable. Because these events are generally of short duration, the screens employed to determine which systems to use must respond at similar time intervals. This is why common computer monitors and televisions are limited by the frequency of screen refresh or scan frequency. As follows, mobile devices such as cell phones or tablets of medium or high range, besides being easy to acquire and widely used, are characterized by high scanning frequencies. Add this to the fact that the high processing characteristics of mobile devices allow a better temporal resolution in these applications. This is why TimeCCam app (Time, Capture, Camera) was developed (available at https://observatorioastronomico.uto.edu.co/observatorio-astronomico-utp-oautp/software-timeccam-para-android.html) for mobile devices. Being compatible with Android operating systems allows a greater reach and wider use by the astronomical community. When running on a cell phone, the characteristics of high frequency scanning and processing allow the visualization of rapid changes in the display. As the majority of cell phones currently have GPS receivers, the application is developed to extract its reference time from the GPS receiver, synchronizing in UTC time.

When the application is initiated by the user, communication with the GPS sensor is carried out internally. Once correct synchronization is established, the panel of squares consisting of an array of 25 rows by 20 columns is activated and the sequence is started (see left side of Figure 3). The first square, located in the upper left corner, is activated in a UTC integer second for 20 ms. After this time, which represents the temporary resolution of the optical stamp, the square is deactivated to continue with the instant activation of the adjacent square of the next row. The successive activation is repeated every 20 ms until the first column of the arrangement is completed, and then continues in an orderly manner with the following columns. The total
Figure 3. Screenshot with the application running and its capture by a camera.

The number of squares represents a complete cycle of 10 s. The start time of the first square in each cycle is shown on the display. This, with the labels that mark the position of each square, allows the UTC time identification in each square. When the focused camera registers the panel during a certain exposure time, a sequence of lit frames is displayed on the captured image (see right side of Figure 3). On this image, the rest of the squares appear deactivated with a color characterized by being identifiable at low exposures, and which does not saturate the image at high exposure times. The positions of the start squares and the end squares of the sequence are decoded to determine the parameters of exposure time, dead time, and jitter.

3.3. Capture of images

A Dell Latitude E6410 computer with intel Core i7 processor, 64 bits, 2.67 GHz, 6 GB of RAM and Windows 10 as operating system was used for the study. Tests were performed using different configurations to determine the incidence of software and hardware on the characteristics and performance of the cameras. MaxIm DL version 6.18 and CCDSoft version 5.00 were used as control software for the CCD detectors SBIG STF-8300M and ST-2000XM. These cameras were synchronized using the NTP protocol through the Dimension 4 software and the Tardis service. In contrast the SharpCap 3.1 was the control software used for the CMOS QHY174M-GPS camera, and the time synchronization was obtained directly from its GPS receiver.

The exposure times used in the test comply with the objective to evaluate the performance of the cameras at common work rates in stellar occultations – for short, medium and long duration events. This is how the exposure times defined were 400 ms, 900 ms, and 1800 ms per camera and software. Likewise, the capture of 50 photographs was established for each configuration since, given the exposure times used, it is possible to cover a wide range of intervals of stellar occultation by smaller bodies of the Solar System. Having a resolution in the time measurement of 20 ms, the uncertainty of said measurement is 20 ms. Finally, a total of 1350 photos were taken by testing 27 different configurations. Figure 4 presents the diagram that summarizes the different configurations used to capture the images.
Figure 4. Schematic of the configurations.

4. Decoding of images
The processing begins with the identification of the start and end moments of the images captured by each configuration. The first characteristic to be identified is the real exposure time, determined by the number of lit squares present in each captured image. Taking the previous value and relating it to the temporal resolution, the real exposure time per image captured is calculated. The second measurement to be made is the dead time of each camera. Due to inactivation during the reading process, between two shots, the route of the squares is interrupted. To determine dead time, it is necessary to compare two consecutive images, identifying the number of squares deactivated between the end of the first and the beginning of the second image. Finally, jitter is determined to measure the accuracy of the synchronization. This parameter is obtained by comparing the time stamp of the application with the stamp given by the configuration of the acquisition system, embedded in the header of the image. In this way, the “Start” (lower left corner of Figure 3) is used as a reference, which marks the instant of time when the square of the position (1,1) was activated. With the previous time and the number of squares up to the capture start position, the capture start time is determined. Thus, when contrasting this standard time with the time of the header, the accuracy of the synchronization method along with the sequence of shots are determined.

5. Results
5.1. Exposure time
Figure 5 presents the exposure times measured for the three cameras in their different configurations. First, no correlation was observed between the measured exposure times and the
configurations used in the cameras in the work. The instability in the exposure times is constant with the increase in the programmed exposure times for the ST-2000XM camera. In turn, it was observed that 4.5% of the shots at 400 ms are outside of the measurement uncertainty (20 ms). For the exposure time of 900 ms, the percentage of shots outside of the uncertainty was 2.5%, and for 1800 ms it was 3.5%. The STF-8300M camera presented a similar behavior to the ST-2000XM, differing in that the stability decreased with the increase of the exposure time. 2% of the shots at 400 ms were located outside of the measurement uncertainty, while for 900 and 1800 ms, 3.5% and 20% were located out of the measurement uncertainty, respectively.

Finally, there is no clear relationship between the stability of the measured exposure time and the increase in the programmed exposure time in the QHY174M-GPS camera. The highest level of stability was obtained at 900 ms in which all shots were found within the region of uncertainty. At 400 ms and 1800 ms images obtained were 4% and 6% outside of this interval, respectively.
5.2. Dead time

In Figure 6 the behavior of the dead time per camera and exposure time for each configuration are presented. The graphs show the existence of a direct relationship between the dead time and the configuration used. In the case of the STF-8300M camera, the minimum dead time recorded is obtained using MaxIm DL as control software and Dimension 4 as the synchronization method. In this configuration, an average dead time of 2719.05 ms was obtained for the three exposure times used. Conversely, the longest dead time for this camera was obtained using CCDSoft as control software and with either of the two methods of NTP synchronization, recording an average dead time of 2948.84 ms.

In the case of the ST-2000XM camera, the best configuration was obtained when performing the control by CCDSoft and the synchronization by Tardis, with an average dead time of 6394.94 ms. The configuration with inferior performance was the set MaxIm DL and Dimension 4, with an average dead time value of 6508.30 ms. Finally, the set ST2000-XM - CCDSof shown
considerable instability in the final shots for the exposure times of 900 and 1800 ms, as can be seen in Figure 7.

It was found that the reading time in the QHY174M-GPS camera is less than the temporal resolution of the application.

![Graph showing dead time behavior for the camera ST-2000XM at 900 ms. MaxIm DL – Dimension 4: Blue circles. MaxIm DL – Tardis: Green squares. CCDSoft – Dimension 4: Yellow triangles. CCDSoft – Tardis: Orange diamonds.]

5.3. Synchronization

Figure 8 illustrates the results obtained when performing the synchronization test. It is observed that the time recorded by the camera QHY174M-GPS tends to advance with respect to the reference time given by the application. It is also observed that the time recorded by the camera is synchronized periodically with the time recorded by its GPS.

On the other hand, both SBig cameras tend to lag, that is, the time given by the NTP synchronization tends to fall behind the time given by the application, as the number of the capture increases. The slope for each of the configurations shows that the synchronization for the STF-8300M camera has a higher delay rate than that of the ST-2000XM camera.

6. Conclusions

The behavior in the three cameras of the measured exposure times showed insignificant differences when considering these instruments for the observation of stellar occultations. This is due to the fact that the maximum difference between the exposure times measured and those programmed is by far twice the value of the uncertainty.

For stellar occultations of short duration, such as those due to trans-Neptunian objects, dead time is a fundamental parameter. This is because very high values in the reading time prevent to determine the precise size of the occulting body. Because of this, the camera ST-2000XM’s dead time characteristics make it inadequate to observe this type of event. On the one hand, the dead times found in the order of 6 seconds are very high for this technique. Second, instability under certain configurations prevents the continuous observation of short events. In the case of the camera of the STF-8300M, a dead time of almost 3 seconds was found, evidencing how the MaxIm DL - Dimension 4 configuration presented the best performance. Despite this, of the three cameras under study, the QHY174M-GPS presented an optimum dead time whose values were within the uncertainty of measurement. This allows us to conclude that while the camera
Figure 8. Measurement of jitter. The first row of graphs corresponds to the data obtained by the STF-8300M camera, the second row to the ST-2000XM camera and the third row to the QHY174M-GPS. The first column corresponds to the tests performed at 400 ms of exposure, the second column to the tests at 900 ms and the third to 1800 ms. MaxIm DL – Dimension 4: Blue circles. MaxIm DL – Tardis: Green squares. CCDSoft – Dimension 4: Yellow triangles. CCDSoft – Tardis: Orange diamonds.

QHY174M-GPS is ideal for observing occultations due to TNOs (fast events), the STF-8300M camera can be used for events of longer duration, as is the case of occultations due to main belt asteroids.

Thanks to its GPS module, the camera QHY174M-GPS periodically updates the time recorded in the images with respect to real time, unlike the SBig cameras where the delay presented increases with the captures. Hence, the QHY174M-GPS is the most appropriate to record stellar occultations with maximum accuracy in the time stamp. For SBig cameras, it is essential to periodically monitor and synchronize the software that communicates with the time server in order to guarantee minimum delays in the recorded times.

Given the correction in the synchronization performed by the camera QHY174M-GPS, in addition to the delays observed for long operating times of the camera, it is necessary to generate strategies that allow to validate the time the application uses as reference time for its synchronization.
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