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Ocultaciones de estrellas por asteroides

Stellar occultations by asteroids

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Resumen: Este trabajo lleva a cabo un estudio de ocultaciones de estrellas por asteroides observadas por los telescopios MAGIC, localizados en la isla de La Palma. Principalmente se analizarán los resultados obtenidos en estas observaciones para determinar su calidad, y así determinar si estos telescopios son adecuados para este uso. Se comienza por definir en detalle los conceptos importantes relacionados con las ocultaciones, que supondrán una base necesaria para la posterior comprensión del análisis. A eso le sigue la descripción del proceso de obtención de las predicciones de estos eventos, que se hacen mediante el programa Occult Watcher y de la librería de Python SORA. Se procede entonces a presentar los resultados obtenidos en las observaciones que se han identificado como exitosas. Por último se pone a prueba el método de fotometría rápida de MAGIC con la ocultación positiva.

Abstract: This work studies star occultations by asteroids observed by the MAGIC telescopes located on the island of La Palma. The results obtained from these observations will be analyzed to determine their quality and, thus, determine if these telescopes are suitable for this use. It begins by defining in detail the important concepts related to occultations, which will provide a necessary basis for the subsequent understanding of the analysis. This is followed by a description of the process of obtaining predictions for these events, which are made using the Occult Watcher program and the Python SORA library. We then proceed to present the results obtained in the observations that have been identified as successful. Finally, MAGIC's fast photometry method is tested with a positive occultation.

Contents

1 Introduction

A stellar occultation occurs when an occulting body, which will solely be an asteroid throughout this text, crosses the observer's line of sight with respect to a star. The study of the shadow resulting from the event can be seen as a drop in the stellar light flux concerning the usual situation; this occurrence can lead to determining physical parameters about the bodies involved in the event with high accuracy, in addition to information about the position and trajectory of said astronomical bodies.

Taking into account that stellar occultations by small bodies have always been difficult to predict and observe, the work preceding the observation has made up a significant part of this study. A reliable prediction demands the accurate position of the occulted star and occulting body, in other words, its ephemeris, along with a deep understanding of a list of parameters that will establish whether the occultation conforms to an observable event from our observing site, the MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescopes located in Roque de los Muchachos Observatory in La Palma. The *Occult Watcher* software has been the primary tool within this part of the job.

The latter analysis of the obtained outcome conforms to examining the light curve resulting from the occultation. The data manipulation and processing have been done using the SORA (Stellar Occultation Reduction Analysis) library in Python. For the sake of comparison, these results have been compared with NASA's Small Body Catalogue.

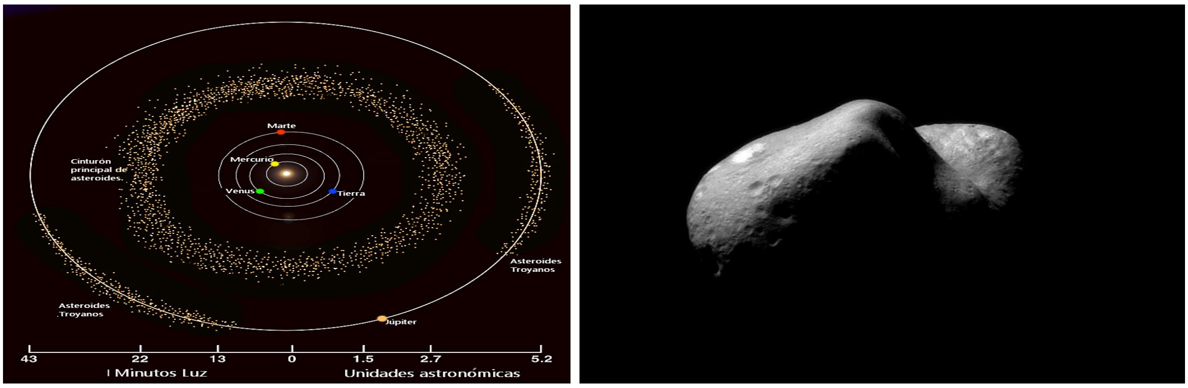
1.1 Basic concepts

1.1.1 Asteroids

The rocky remnants of material left over from the solar system's formation about 4.600 million years ago have been given the name asteroids. This word of Greek origin translates to "star-like" and was coined by William Herschel in 1802. The event that pushed the astronomer to propose the creation of a new astronomical term was no other than the discovery of Ceres. Even though it was initially thought to be a new planet, the small size and lack of planetary disk, along with the rapid discovery of other similar bodies, pointed researchers towards creating a separation in terminology for them.

The term Asteroid does not have a formal definition but rather shares, along with comets and meteorites, the broad term small Solar System bodies. Thus, the label asteroid is applied to the irregularly shaped rocky bodies that orbit the Sun but do not qualify as planets or dwarf planets, taking into account that the distinction between comets and them relies on the fact that comets show a coma due to the sublimation of ice in their surfaces.

The appearance of these bodies varies widely both in shape and size. Among the at least 1,351,400 asteroids currently known, most exhibit an irregular shape, even though some have a surprisingly spherical look. Similarly, size differs significantly, with the largest being Ceres, which is classified due to its dimensions as a dwarf planet. For that reason, the classification turns upon the differences in compositions. There are three main types: C-type, M-type, and S-type, corresponding to carbonaceous, metallic, and siliceous compositions.



(a) (b)

Figure 1: (a) Location of the Asteroid belt in the Solar System [1] and (b) 433 Eros asteroid [2].

For the main part, asteroids can be found orbiting within the asteroid belt, that is, between the orbits of Mars and Jupiter. Even though, contrary to popular belief, this area of the Solar System is mostly empty, it is estimated to contain between 1.1 and 1.9 million asteroids larger than 1 km in diameter and many smaller ones. These bodies could have been accreted as planets if the presence of Jupiter had not prevented it. Moreover, we can find many asteroids in the Lagrange points of stability L4 and L5 in Jupiter's orbit. It is essential to note the existence of asteroids whose orbit passes close enough to that of Earth, which receive the name of Near-Earth asteroids. Within this category, we can find some that have a probability of collision with our planet.

The Minor Planet Center (MPC) handles the discovery of a new asteroid. It assigns a provisional name to the object and a number, which does not have to be its discovery order. After that, research takes place to study its orbit with sufficient precision to predict its trajectory. Later, the discoverer chooses the final name, which must be approved by the International Astronomical Union (IAU).

1.1.2 Stars

Stars can be considered the fundamental building blocks of galaxies. Therefore, the study and understanding of these astronomical objects provide an elemental starting point for the consequent analysis of events in which they are involved. In the context of this text, we will pay close attention to specific parameters of these bodies, particularly their luminosity and size. According to them, the corresponding classification uses Roman numerals where classes I and II designate supergiants, class III giants, class IV subgiants, and class V the dwarfs of the Main Sequence. Other classes, such as VI and VII, designate subdwarfs and white dwarfs, which will not be helpful in this work.

Throughout this text, the concept of magnitude will be mentioned regularly. We will work with two distinctions of it: apparent and absolute magnitude. Even though both ideas refer to the brightness of a star, they differ in their definitions. The apparent magnitude depends on an object's brightness and its intrinsic luminosity, its distance, and the extinction reducing its brightness. The absolute magnitude describes the intrinsic luminosity emitted by an object and is defined to be equal to the apparent magnitude that the object would have if it were placed at a certain distance, 10 parsecs for stars.

It has been necessary to collect information regarding the positions of the stars and other features, which are compiled in various star catalogs accessed through the VizieR2 database [3]. The stars that are relevant for this work have been found within the Gaia DR3 (the third version of data published by the mission of the Gaia satellite of the European Space Agency (ESA)) and the UCAC4 (Fourth US Naval Observatory CCD Astrograph Catalogue), which contains the physical characteristics of about 113 million stars.

1.1.3 Ephemerides

In celestial navigation and astronomy, it is essential to have access to data describing celestial bodies' trajectories. For that purpose, we rely on ephemerides, which include parameters such as the position and velocity of the body in question over some time [4]. If applicable, the astronomical position calculated from an ephemeris is often given in the spherical polar coordinate system of right ascension and declination, along with the distance from the origin. In particular, the ephemerides used throughout this work were calculated with respect to the barycenter of the Solar System.

In the context of this work, to correctly predict and analyze the occultation events, we have worked with the ephemerides of several asteroids, which have been obtained thanks to the Horizons System's astronomical object tracking and prediction system developed by NASA's Jet Propulsion Laboratory (JPL) [5]. JPL's Solar System Dynamics (SSD) group is part of the Mission Design and Navigation section. This group focuses on determining the motion and physical parameters of natural planetary objects, such as accurate position and velocity histories (ephemerides), gravity fields, and rotational parameters for solar system bodies, including the planets, planetary satellites, asteroids, and comets; providing not only the physical parameters of the trajectories but also the corresponding uncertainties.

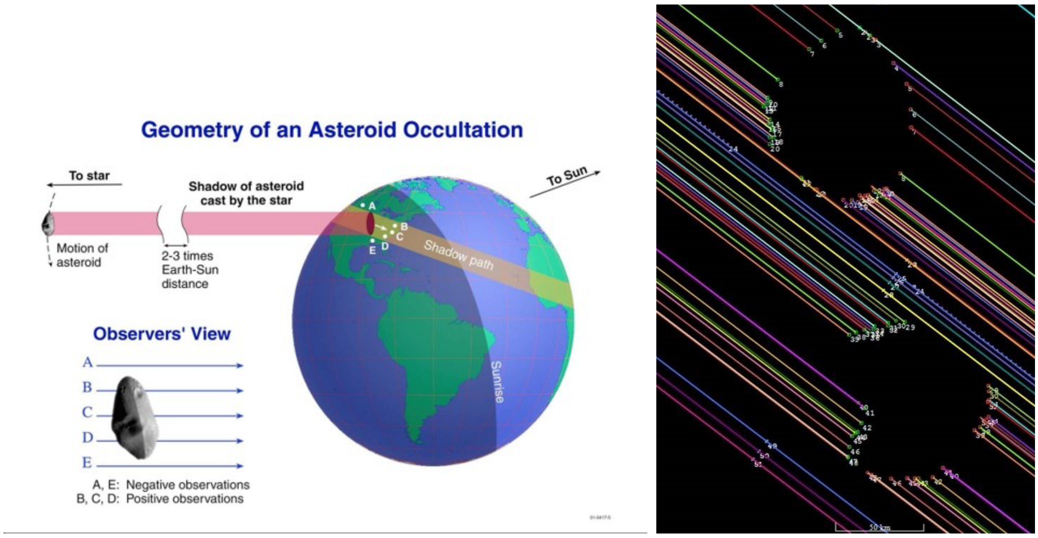
Additionally, the calculations required information about the asteroids' orbit with respect to the position of the Earth's center, which was acquired thanks to the SPICE information system (Spacecraft Planet Instrument C-matrix Events) developed by NAIF (Navigation and Ancillary Information Facility) from NASA. This public access platform provides a geometry information system to assist scientists in planning and interpreting scientific observations.

1.1.4 Occultations

When two celestial bodies appear aligned for an observer at a point on Earth, different situations can take place depending on their apparent sizes. These phenomena can include eclipses, transits, or occultations. The eclipse occurs when the bodies have an almost equal angular size, resulting from the involvement of bodies such as the Sun and the Moon. The transit is the interposition of a body of smaller apparent size to another larger body [6]. In this case, the disappearance of the most distant body does not occur; rather, it is a passage or transit of the first projected onto the surface of the larger one. For example the transits of Mercury and Venus through the solar disk. Lastly, an occultation is the interposition of a body of apparent size larger than another smaller body. The body that produces the occultation blocks the light of the distant object. There are several types of occultation depending on the bodies that intervene: satellites for planets, of planets for the Moon, of stars for the Moon, of stars for planets or stars for asteroids.

Occultations have been used since the invention of telescopes to determine the position of the Moon, time, and the observer's position in the sea. The observation of these events is used to determine the positions of stars, radii, and other parameters. For this one work has analyzed occultations of stars by asteroids.

When the phenomenon of the occultation of a star by an asteroid is observed, there is a fall of the magnitude observed in the direction of the star. In most cases, the star hidden is brighter than the asteroid, so the decrease in brightness reaches the magnitude of the asteroid. This drop in magnitude can be recorded visually or using electronics such as video, photometers, or CCD (Charged-Couple Device). As the asteroid follows its orbit, it generates a shadow of the star's light on the surface of the Earth. It is important to note that this type of occultation lasts from a few seconds to a few minutes, depending on the differences of angular velocity between the Earth and the asteroid and their distance.



(a) (b)

Figure 2: (a) Geometry of an asteroid occultation (Image created by IOTA) [7] and (b) Measurements of the lengths [8].

As a result of the analysis of the occultations, we can measure the size and shape of the asteroid, by observing the void of his shadow. We can also characterize its orbit, that is, check its ephemeris and update the orbital gravitational jamming elements, knowing the instant of occultation. At the edges of the occultation light curve, we obtain Fresnel's diffraction pattern projected onto the Earth's surface. By bringing into play our knowledge of this optical phenomenon we can obtain the angular size of the star and the asteroid. In addition, we can obtain details of the key importance of binary star systems and identify structures in asteroids as bodies with rings or satellites.

To conclude this introduction to these events, we proceed to briefly study the geometry behind occultations. For that purpose, we are going to work with the diagram shown in Figure 3. In this representation, we are denoting the star as S, along with the positions of the asteroid, which are B_1 and B_2 obtained from the corresponding ephemeris at time t_1 and t_2. Similarly, the Δ magnitudes represent angular separations: Δ_1 and Δ_2 are the star angular separation to B_1 and B_2, respectively and Δ_B is the angular separation between the ephemerides. The distances that are represented in the image are CA, which is the distance of the closest approach, and PA, which is the position angle of the body's closest approach to the star.

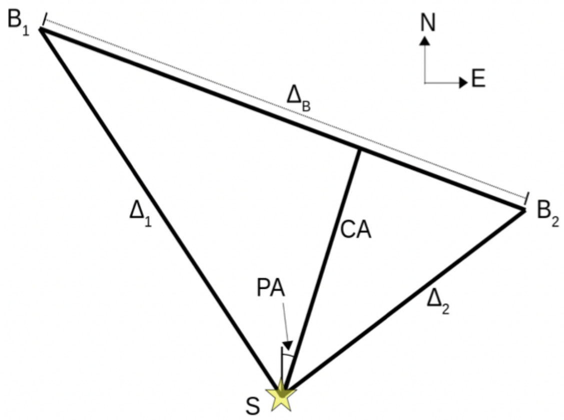


Figure 3: Diagram representing the geometry behind an occultation event [9].

Just as the previous diagram shows, for us to be able to make an accurate analysis of the occultation events, it is essential to examine in contrast our predictions, which are made by making use of the software *SORA*, with an external prediction. This comparison allows us to have data regarding identifying parameters about the star and asteroid and gives us the possibility to better refine our predictions based on them. Once we have at our disposition the ephemerides of the bodies involved, we can obtain the following parameters:

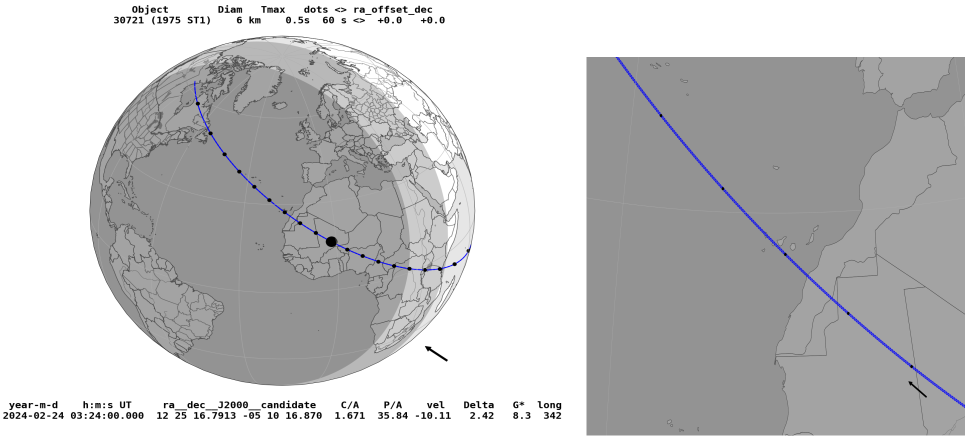
- Taking into account that the magnitude of the distances allows us to treat the light rays coming from the star as parallel, we can approximate the **width of the shadow cast on the Earth's surface** as the size of the asteroid. Due to the usual irregular shape of these astronomical bodies, depending on the position of the observer a different width can be measured. These length values can be fitted to an ellipse and the resulting combination gives an accurate idea of the asteroid's shape.

- Due to the size and velocities of asteroids the **duration** of the actual occultations is usually between 0.5-10 seconds. The time of occultation that we will refer to as TOA will correspond to the time at which the asteroid stops occulting the star. To analyse our results we will use this duration time to estimate the diameter of the corresponding asteroid.

- Taking advantage of our knowledge of the geometry behind an occultation event, and under the assumption that the light of the star is the only one taking part in the event, we consider the **shadow that the asteroid will project on the Earth's surface**, which will travel in a linear path concerning the observer. Throughout our calculation, we will require the value of the velocity of that shadow.

- **Moonlight** can interfere with the data collected during the observation. For this very reason, the phase of the Moon at the time of the occultation has been a determining parameter. The ideal situation takes place when the Moon is under the horizon or at a far enough distance. Similarly, to avoid the **Sun's light** from getting in the way of our results, we have only considered occultations in which the Sun's position is 18 degrees below the horizon.

- Just as we previously mentioned, there is a **magnitude drop** between the moment right before the occultation, in which both bodies contribute with their magnitudes, and during the event, when the asteroid passes right in front of the star decreasing the coming light flux from the perspective of our telescope.



(a) (b)

Figure 4: (a) Map of the shadow cast by the asteroid on Earth's surface (obtained with Occult Watcher Cloud) and (b) Zoom of the asteroid's shadow.

By using the SORA library in Python, we obtained a map of the predicted path in which the occultation could be observed. As the events are already filtered, this one passes right through the location of our observing telescope, located in one of the Canary Islands.

2 Goals

The analysis of star occultations provides valuable information for several fields of study. For instance, it supports research about planetary formation by collecting information about asteroids that can help decipher unknowns about the formation process of planets and other objects in the Solar System. Additionally, it also may be of importance to study NEOs (Near Earth Objects). Astronomical objects, such as comets or asteroids, whose trajectories come close enough to Earth, become a part of this category, and by studying occultations, we gain important knowledge about parameters that help define whether they represent a danger to the planet.

Our main objectives within the context of this text will be to observe the occultations we have predicted and measure their parameters. The results of these calculations will allow us to derive different characteristics of the astronomical bodies, both the asteroid and the star, that take part in the event. Finally, by understanding and comparing our results to those of others, we can get an idea of the quality of our results, along with gaining crucial insight about how to improve and upgrade the different steps of our methodology to enhance the elements that conform to the event.

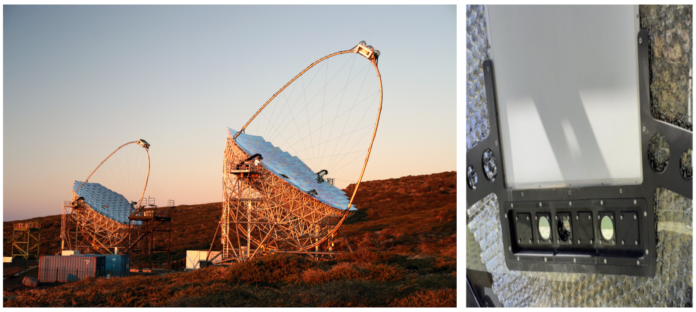
Additionally, we want this work to test the newly developed method of MAGIC interferometry for the purpose of observing the occultations. Furthermore, we will be implementing fast photometry to analyse these events, which is still a developing technique.

3 Methodology

3.1 MAGIC Interferometry setup

As was already mentioned throughout the text, the telescopes used to observe the occultations were the MAGIC telescopes. This pair of telescopes was initially designed to detect gamma radiation originating in extragalactic sources. The MAGIC set is located in the Roque de los Muchachos Observatory, in the Canary island of La Palma, over 2200 m above sea level. In 2004 MAGIC I began its observations and later, in 2009, MAGIC II was built; both have a diameter of 17 m and are separated by 85 m.

However the MAGIC telescopes have lately been used to implement optical intensity interferometry techniques. This method relies on using several telescopes to obtain a higher resolution than they would obtain individually by correlating their signals. Implementing new-generation instrumentation has allowed this system of two IACTs (Imaging Atmospheric Cherenkov Telescopes) to perform intensity interferometry observations. In turn, the technical modifications introduced have made it possible to use them for fast optical observations of the type needed to observe occultations.



(a) (b)

Figure 5: (a) MAGIC telescopes in the Roque de los Muchachos Observatory [10] and (b) Hexagonal light concentrators behind the filter holder and the diffusive white target in a close-up of the MAGIC telescope's surface [1].

We will briefly describe the alterations made to adapt the telescopes for interferometry observations of stars.

In the first place, opposite to standard VHE observations, narrow-band optical filters have been installed before the camera. The need to install these devices comes from the brightness of the observed star, which can damage the camera photo multipliers (PMTs) after a short time, these filters protect them and are also needed for reasons beyond this work.

In addition, Intensity Interferometry requires continuous digitization and correlation of the recorded data. This has been achieved by the incorporation of a set of fast digitizers and a GPU-based correlator. These particular digitizers make direct data transfers between the digitizer's memory and the GPU's memory possible, eliminating the need for intermediate copies and making the whole process much more efficient.

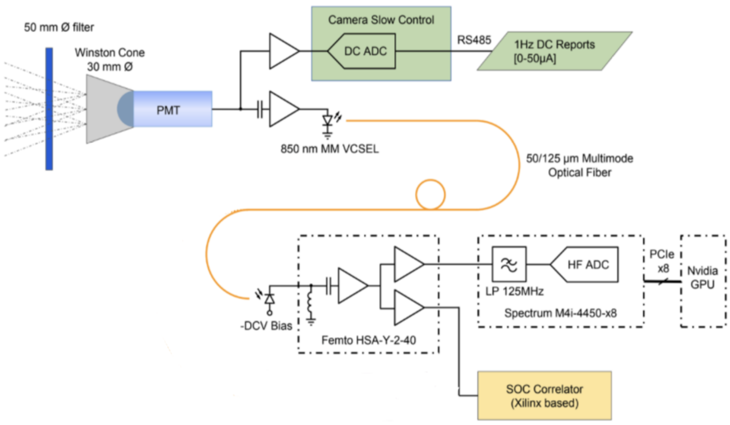


Figure 6: Diagram describing the components of the MAGIC II setup.

3.2 Software

The utilization of certain programs has been key before and after the observation.

To begin with, the predictions that allowed us to obtain the results of the telescopes at a certain time were made using the Occult Watcher (OW) software. This program, only available for MS Windows, provides free and open access to occultation predictions based on the position of the observer. A regular check-up of the posted predictions was necessary to establish a schedule each month. Through this program, we were able to set up a series of filtering parameters, which we will discuss further on. In addition to the desktop application, we also used the web version, Occult Watcher Cloud, which provides direct access to star catalogs and maps of the sky. The main sources of occultation predictions that were used throughout this work were:

- IOTA (International Occultation Timing Association): It is the leading worldwide organization for data collection on occultations. The predictions are gathered by a group of volunteers and reported on the organization's web page. Following the events the page also collects important information captured in the observations.
- IBEROC: A source that is led by Carles Perello of the Sabadell Astronomical Group. It provides occultations and their observable predictions of the Iberian Peninsula, the Balearic Islands, and the Canary Islands.

In addition to this program, the data resulting from the observations were analyzed using a Jupyter Notebook initially provided by Tarek Hassan (CIEMAT) and which we adapted and modified.

3.3 Observations and analysis

It was necessary to establish selection criteria to filter plausible occultations from the many possible ones detected by the Occult Watcher software. The first was the magnitude of the combined system formed by the star and the asteroid. If the system were too dim, the telescope would not detect it. We established a limit of 12.5-13.0 magnitudes for it. Given the angular size of MAGIC pixels, both objects remain inside the pixels' Field of View during the whole observation.

The first and very clear constraint was that the event had to have a high probability of being seen from the location of the Observatory. Asteroid ephemerides have relatively large uncertainties, making the predictions of occultations always a process of probabilistic nature. The track of the asteroid over the Earth can be seen as the center of a Gaussian whose width is the size of the uncertainties in the trajectory. On both sides of this Gaussian, we add half the size of the asteroid, and the uncertainties on the asteroid size. Then, the probability of observation is obtained by integrating the distribution over the possible trajectories for which the observer would be inside the shadow. The probability is computed by OW, and we limited our chosen events to those having at least a 60% probability.

The concepts defined in section 1.1.4 are of use to us in this section as they represent some of the qualifying parameters to consider while deciding which observations are worth a chance.

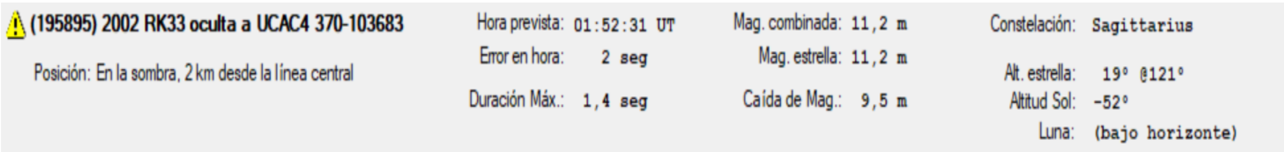


Figure 7: Screenshot of the program Occult Watcher with the displayed parameters about an occultation.

The magnitude of a star is of main significance in determining whether an observation is viable. The characteristics of our observing telescopes establish the limit of the stars' brightness in the event. This limit is about magnitude 12; above that number, the star would be too dark to be observed. Similarly, the magnitude drop at the moment of the occultation has to be significant, which means above 2.0 or 2.5 magnitudes, so we can capture it. In addition the star shouldn´t be too close to the horizon, as background light is stronger there.

As we previously mentioned, the Sun's position was considered adequate when it was at least 18 degrees below the horizon, so sunlight did not interfere with the obtained data. Moreover, the Moon's position also played a part in the decision. Ideally, the Moon would be either below the horizon or at a considerable angular distance from the star involved in the event, which is at least 45 degrees. If the Moon was present, it should have a low illumination (full Moon periods were rejected).

After the occultations were selected following these parameters, we checked its parameters using a Jupyter Notebook based on SORA and a petition was sent to the MAGIC scheduler to ask for their observation. The time intervals that we considered to include the uncertainty of the occultation times and possible delays in the observation were 10 minutes before the event and 5 minutes after it, giving a time window to cover for possible errors.

If the telescopes were not being used for experiments of higher priority at the given time and the weather conditions were favorable, the observations would be made, and we would be able to download a data file containing the results.

The Jupyter Notebook that we have previously mentioned now comes into use. The code reads the data from the file, identifies the occultation interval, averages the signal over several samples to reduce the noise and creates plots. The original script has been modified to include different plots on which the results shown in this work are based.

4 Results

4.1 Predictions and observations

Beginning in February 2024 and throughout May 2024, we collected a series of possible occultations following the criteria already explained via the OccultWatcher software. In the following table, we have collected all 13 possible occultations along with some of the previously mentioned parameters. Most events have a high probability of observation, and those that do not were included, as the rest of the parameters seemed promising enough.

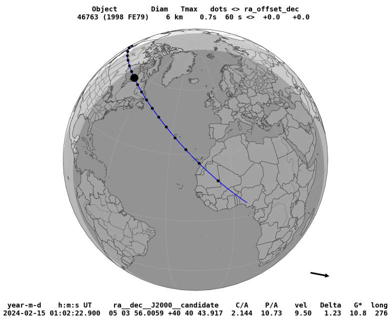
Number of event	Result of observation	Asteroid Name	Event Date, UT	Star Name	Star Mag	Duration (s)	Mag Drop	Star Alt (º)
1	Observed, positive	(46763) 1998 FE79	Thu 15 Feb, 01:11 UT	UCAC4 654-027702	11.7	0.7	6.2	34
2	Not observed	(2137) Priscilla	Mon 19 Feb, 04:23 UT	UCAC4 551-044990	10.1	3.0	5.8	29
3	Not observed	(30721) 1975 ST1	Sat 24 Feb, 03:27 UT	UCAC4 425-056850	9.1	0.6	10.1	56
4	Observed, negative	(83674) 2001 TP41	29 feb. 2024 03:34:19	HIP 30862	7.0	1.3	12.3	12
5	Not observed	(568) Cheruskia	Thu 07 Mar, 20:12 UT	TYC 1225-01340-1	11.4	2.1	3.5	49
6	Not observed	(41694) 2000 UT41	07 mar. 2024 20:35:44	TYC 1325-00556-1	11.0	0.6	3.0	81
7	Observed, negative	(969) Leocadia	Sat 06 Apr 00:04 UT	UCAC 363-067089	12.5	1.5	4.7	31
8	Observed, negative	(15489) 1999 CJ78	Tu 10 Apr, 05:02:55 UT	UCAC4 376-132058	12.8	1.5	6.3	41
9	Observed, negative	(195895) 2002 RK33	Wed 11 Apr, 01:52:31 UT	UCAC 370-103683	11.2	1.4	9.5	19
10	Observed, semi-positive	(31675) 1999 JO10	Fri 03 May, 03:49:42 UT	G185437.4-141611	10.7	5.7	8.7	41
11	Observed, negative	(29199) Himeji	Mon 06 May, 23:28:12 UT	TYC 6116-00653-1	11.4	1.3	5.7	43
12	Observed, negative	(801) Helwerthia	Wed 08 May, 23:03:19 UT	UCAC4 503-049935	12.1	1.4	4.4	27
13	Observed, negative	(160363) 2003 YP107	Fri 17 May, 04:12:33 UT	TYC 7373-00055-1	10.0	0.6	9.7	21

Number of event	Moon Alt (º)	Moon Dist (º)	Moon Illum (%)	Sun Alt (º)	Sun Dist (º)	Prob (%)	Shadow	1sigma
1	-11		33	-74		92,20%	6	9
2	1	37	75	-45		99,90%	36	41
3	56	37	100	-56		79,40%	7	12
4	46	116	82	-53		48,70%	22	37
5	-48		10	-13	62	100,00%	73	75
6		139		-18	104	87,60%	6	8
7			33	-74		100,00%	19	22
8			3	-23		54,30%	23	25
9				-52		41,10%	22	61
10	4	53		-31		100,00%	16	18
11				-38		79,80%	19	21
12				-35		76,80%	34	36
13				-24		86,90%	13	19

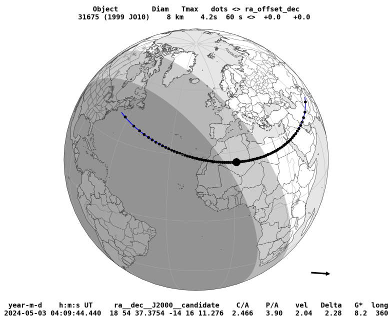
Table 1: Table that includes all the parameters for the observations provided by the OccultWatcher software. Along with the names of the objects involved in the occultation and some defyning features (magnitude and altitude of the star at the time of the event), we can also find the duration and magnitude drop in the first table. The second table contains the parameters associated with the observation: to have an idea about the influence that the Sun and the Moon will have in the results we have data about their altitude and distance at that particular time in addition to the Moon's illumination. The distance from the observatory to the actual shadow of the asteroid and the first sigma showing its uncertainty can also be found in the table.

In addition to the data provided by OccultWatcher, we have used the prediction module of the Python library SORA. For each prediction, we made a small program in which we provided the corresponding ephemeris of the asteroid in a wide time interval around the date of the future occultation along with the position data of the Earth concerning the barycenter of the Solar System and the position of the observer, in our case the coordinates of the MAGIC telescopes. This program uses that information to generate a table with parameters of the event, some already provided by OW that will be useful to compare and verify that are correct, and other extra data such as speed and shadow width to complete the analysis. In addition, the program also provides us with maps of the trajectories of the asteroid's shadow.

Throughout the description of the occultation events we have been making allusions to the magnitude drop, this drop is, by definition, the result of subtracting the magnitude of the asteroid from the combined magnitude of both the asteroid and the star. This concept is quite intuitive to interpret. We have to take into account that the size of the MAGIC pixel captures both objects involved in the occultation (it can even include some objects that are not taking an active role, but their presence influences the final results), which accounts for the initial combined magnitude, but at the exact moment of the occultation, the asteroid fully occults the star, making the received flux in that moment only due to the brightness of the asteroid. This is why we have looked for bright star occultations by dark-appearing asteroids, which would lead to higher magnitude drops that are easier to observe.



(a)



(b)

Figure 8: Map of the shadow cast by the asteroid on Earth's surface (obtained with Occult Watcher Cloud for (a) 1998 FE79 and (b) 1999 JO10.

For the observations that came out properly, We downloaded the data files with a sampling frequency of around 2 kHz, that is, with 2,000 samples per second. Data files have a binary format; their full content will explained later in section4.4; schematically, they contain the time stamp and photometry information in both telescopes for the pixel viewing the star and a reference background one.

It is important to note that out of the thirteen proposed observations, four of them were not carried out due to weather problems. Furthermore, only two of the remaining nine occultations showed signs of a possible event taking place. We will examine those two occultations in the following sections.

4.2 Analysis of the observed occultations

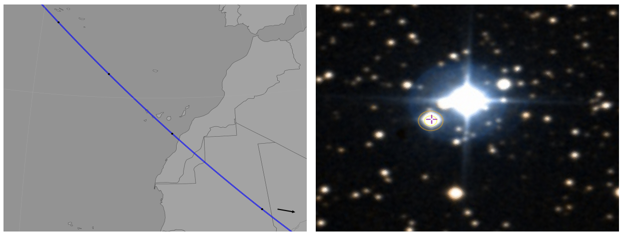
4.2.1 1998 FE79

The occultation of the UCAC4 654-027702 star by the asteroid (46763) 1998 FE79 was predicted to take place at 01:11:01 UT on February 15Th. The estimated maximum duration of the event was 0.77 seconds, and the probability of observing it from the Roque de los Muchachos Observatory was 92.2%.

The asteroid involved in this occultation was discovered on the 24th of March of 1998 by the Lincoln Near-Earth Asteroid Research (LINEAR) observatory, a project born as a collaboration between NASA and the Massachusetts Institute of Technology, which is responsible for the majority of asteroid discoveries from the late nineties to the early two thousand. Some of its physical characteristics that this research could derive include an apparent magnitude of 14.85 and a diameter of 6.4 ± 2.0 km.

The UCAC4 654-027702 star can be found along with its defining parameters in the Fourth U.S. Naval Observatory CCD Astrograph Catalog. Even though it is not a particularly bright star, in light of its apparent magnitude of value 11.73, it is not too dim either, and its contrast with that

of the asteroid has allowed us to obtain sufficient data to confirm the observation of the event. A particularly intriguing aspect of this star can be observed in Figure 9 (b): its proximity to star UCAC4 654-027688. Unlike its stellar neighbor, this star is considerably brighter, with an apparent magnitude of 8.76.
To check whether this substantially luminous background has impacted our results, we have estimated calculations of the magnitude drop with and without the contribution of the bright nearby star. Considering a background star of approximately magnitude 8, we have concluded that the ratio between the light flux after the occultation and before is about 16 times smaller than without considering the UCAC4 654-02768 star. The effect of the background on the results that we have obtained will be discussed in more detail in section4.3.



(a) (b)

Figure 9: (a) Map of the shadow cast by the asteroid on Earth's surface (zoomed into the Canary Islands) and (b) Map of the sky with the star UCAC4 654-027702 at the center and star UCAC4 654-027688 to its right (Obtained with Occult Watcher Cloud).

The graph shows data obtained from three different sources. From MAGIC-I, we have the signal from two PMTS: the one that is measuring the flux coming from the region where the event is taking place, which is represented in orange, and a nearby one measuring a different patch of the sky whose flux should be stable, which is represented in green. Moreover, we have the signal from a PMT in MAGIC-II centered on the occulted star represented in blue. From the graph, we can derive that the duration of the event was approximately 0.5 ± 0.1 seconds. Joining the

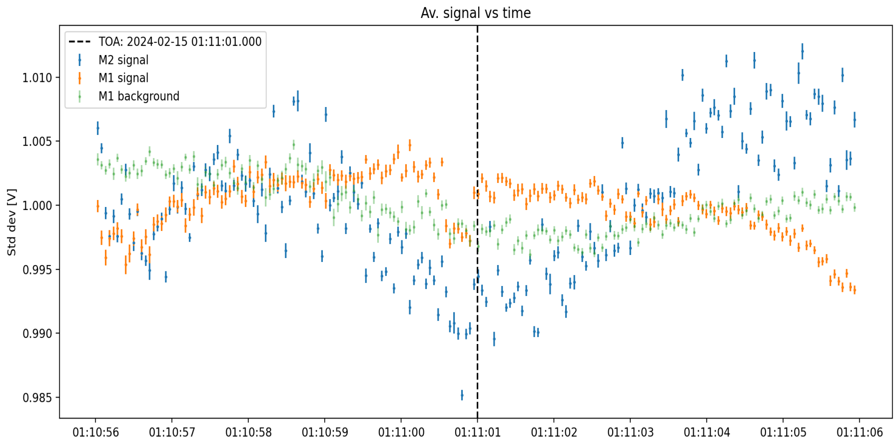


Figure 10: The first graph represents the standard deviation of the complete data set collected by the telescope versus the exact time at which they were received.

information that we were able to extract from the SORA library regarding the velocity at which the shadow cast on Earth's surface by the asteroid was moving, which had a value of 9.5 km/s, with

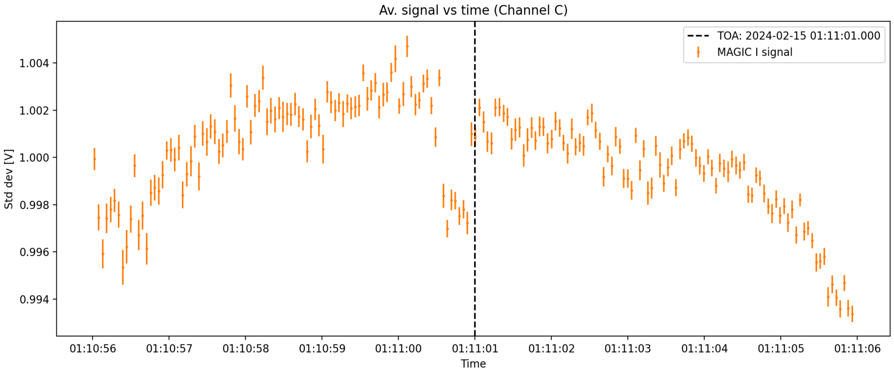


Figure 11: Isolated MAGIC I signal to observe the occultation better. The dotted line shows the predicted time of occultation.

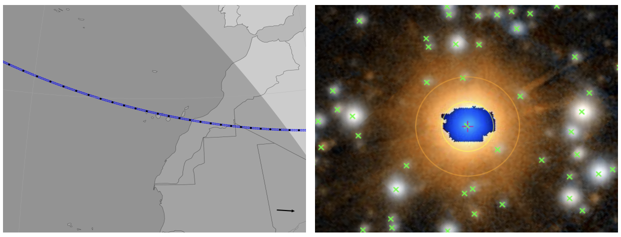
the experimental duration of the occultation event, that we considered to be of 0.5 ± 0.1 seconds, we can easily obtain an estimation for the diameter of the asteroid. The calculated value for the diameter seems compatible with the value obtained from NASA's Small-Body Database.

Asteroid Name	Star Name	$t_{max-predicted}$ (s)	$t_{measured}$ (s)	v_{shadow} (km/s)	$d_{predicted}$ (km)	$d_{measured}$ (km)
(46763) 1998 FE79	UCAC4 654-027702	0.7	0.5	9.5	6.4 ± 2.1	4.75 ± 0.95

Table 2: Values for the duration of the occultation and the diameter of the asteroid.

4.2.2 1999 JO10

The occultation of the G185437.4-141611 star by the asteroid (31675) 1999 JO10 was predicted to occur at 03:49:42 UT on May 3rd 2024. The estimated duration of the event was 5.7 seconds, and the probability of observing it from the Roque de los Muchachos observatory was 100.00%.
The asteroid involved in this occultation was discovered on May 8, 1999, at Catalina Station, an astronomical observatory located in the Santa Catalina Mountains, approximately 29 kilometres northeast of Tucson, Arizona, by the Catalina Sky Survey project. This asteroid has a magnitude of 14.2 and an estimated albedo of 0.056, allowing a diameter of 8.475 ± 0.227 km to be calculated. These results were obtained thanks to observations from the Wide-Field Infrared Survey Explorer (WISE), an American space telescope put into orbit in 2009 and observing the entire sky in infrared, and published in 2011 in an article presenting the first results for main belt asteroids.



(a) (b)

Figure 12: (a) Map of the shadow cast by the asteroid on Earth's surface (zoomed into the Canary Islands) and (b) Map of the sky with the star UCAC4 654-027702 at the center and star UCAC4 654-027688 to its right (Obtained with Occult Watcher Cloud).

Regarding the G185437.4-141611 star, it is one of the stars discovered by the Gaia Collaboration around 2020 and belongs to the catalog Gaia EDR3. It can be said that it is a bright star with a magnitude of 10.7. As seen in the image 12 b below, the star's brightness is quite striking with respect to its background.
As we explained in the previous occultation, we have constructed a graph containing the MAGIC-I signal and background and the MAGIC-II signal to check whether the data obtained from the occultation captures it. From the graph, we can derive that the duration of the event was approximately 5.5 ± 0.2 seconds.

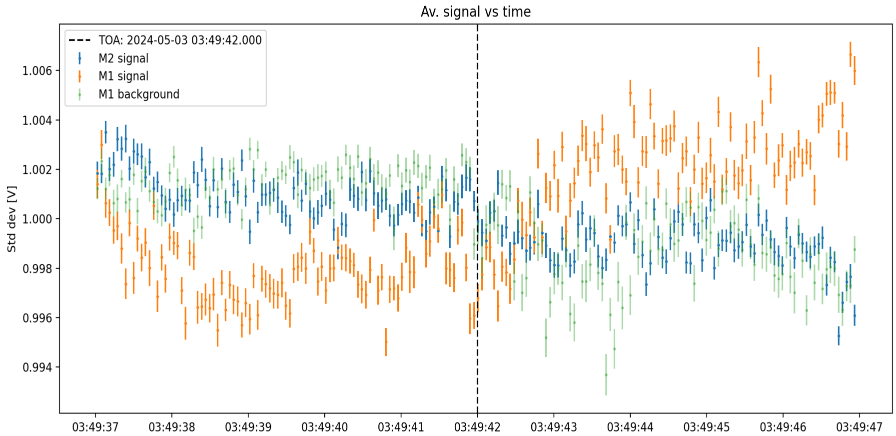


Figure 13: Representation of the standard deviation of the complete data set collected by the telescope versus the exact time they were received. The dashed line shows the predicted time of occultation.

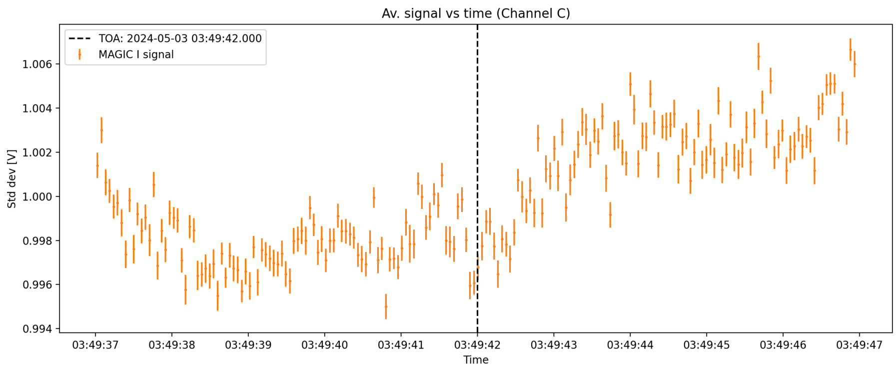


Figure 14: Isolated MAGIC I signal to observe the occultation better. The dotted line shows the predicted time of occultation.

Joining the information that we were able to extract from the SORA library regarding the velocity at which the shadow cast on Earth's surface by the asteroid was moving, which had a value of 2.04 km/s, with the experimental duration of the occultation event, that we considered to be of 5.5 ± 0.2 seconds, we can easily obtain an estimation for the diameter of the asteroid. The calculated diameter value is incompatible with the value obtained from NASA's Small-Body Database, adding uncertainty to our observation.

Asteroid Name	Star Name	$t_{max-pred}$ (s)	$t_{measured}$ (s)	v_{shadow} (km/s)	$d_{predicted}$ (km)	$d_{measured}$ (km)
31675) 1999 JO10	185437.4-141611	5.7	5.5	2.04	8.47 ± 0.23	11.22 ± 0.41

Table 3: Theoretical and experimental values for the duration of the occultation and the diameter of the asteroid.

4.3 Effect of the background light

While discussing the data obtained from the observation, it was briefly mentioned that the environment surrounding the star that takes part in the occultation can influence the outcome. Observing occultations with MAGIC has several limitations: electronic noise, signal instability, and the large size of the pixels. All of them determine the photometric sensitivity of the telescope. We will only consider the last one.
We are going to study the drop in magnitude predicted further. The main issue of the one predicted by OW is that it does not consider the large size of the MAGIC pixel, as it works under the ideal assumption that the pixel has the perfect size only to include the asteroid and the occulted star. However, the MAGIC pixel is large, with a radius of around 0.1° which corresponds to a surface of approximately 400.000 sec^2: Therefore, it integrates a huge amount of Night Sky Background light (NSB), and it may happen that it also includes other bright stars in the field in addition to the occulted one, as we have seen in the case of FE79 (9b). In addition, when the Moon is visible in the sky, its scattered light greatly increases the NSB. The scenarios that we are going to study are the ideal one, the presence of a star as the one seen in FE79, the influence of the NSB, and the presence of the Moon with the parameters seen in the occultation of 1999 JO10. These circumstances lead to the observed luminosity drop during the occultation being much smaller than predicted.

To consider the size of the MAGIC pixel, we simplify its shape by making it circular. If we use a night sky background magnitude of approximately 21.8 m, the optimal one for the ORM observatory [11] on a night, we can estimate that the equivalent magnitude of the sky for the corresponding pixel is about 7.7 magnitudes. If the Moon is visible with the parameters of the JO10 occultation, with 39% illumination and at an angular distance of $\approx 50°$ the NSB magnitude is closer to 20.2. The estimation was obtained following the model described in [12]. Its integrated value in a pixel corresponds to a star of magnitude 6.2. Therefore, the large size of the pixel we are using to observe the events adds a background noise equivalent to the one we would have if we were observing a star with a very bright neighbour.

During a stellar occultation by an asteroid, the moment just before the event, we see the luminous flux coming from the asteroid and the star. When the occultation occurs, we only see the asteroid's flux. From these numbers, we derive the magnitude drop, which was already defined as the difference between the combined magnitude of both objects and that of the asteroid. The more realistic model we propose adds the background magnitude to the calculations, which, as we will see, is dominant.

To get an idea of the actual influence of this effect on the results, we have performed a series of estimations using the data collected during the 1999 FE79 occultation (see section 4.2.1); the results of the calculations have been collected in the following table.

We conclude that the large pixel size pollutes the observation data, adding a background brightness of the same magnitude as that of a close bright star, making it more difficult to perceive the occultation. Of course, the effect is larger when observing with the Moon, even with partial illumination. The effect is very important and limits MAGIC's photometry capabilities.

The numbers in the last row can be compared with the graphs that show the light curve during the occultations, such as 4.2.1. If the occulted star has a magnitude close to 12, as in 4.2.1, the flux is expected to drop by approximately 2.5%. In reality, the drop observed was smaller, of the

	No background	Bright Star	NSB	Partial Moon at 50°
Mag. before the event	11.696	8.157	7.747	6.169
Mag. after the event	17.900	8.200	7.776	6.176
$\Delta Mag.$	6.204	0.042	0.029	0.007
Flux ratio	0.003	0.962	0.974	0.994

Table 4: The 1999 FE79 occultation parameters in four different scenarios: not considering any background, with a bright star in the FoV, considering just the residual brightness of the night's sky, and observing with partial Moon at 50° distance.

order of 0.5%, which the additional noise sources can explain, as commented at the beginning of the section. A similar calculation applied to a star of magnitude 10 provides a drop of around 12%, with a much larger signal-to-noise ratio. An occultation of such a star would be clearly observed and perhaps allow us to measure the star parameters.

4.4 Analysis of the performance of MAGIC´s Fast Photometry mode

Fast Photometry methods with the MAGIC telescopes are a technique still in development. We will use the data collected to draw some preliminary conclusions about it, not pretending to be exhaustive.

As a first thought, it is clear that MAGIC telescopes are not suited for photometry. A photometric measurement requires integrating the light signal received over a certain interval. The MAGIC telescopes were designed to detect the fast Cherenkov pulses with a length of a few nanoseconds. Due to the size of the PMTs, these pulses come on top of a large background, as we have seen in the previous section. To reduce the noise, the continuous component of the current generated in the PMTs, due to the background, is filtered, and only the fast-varying component is used. This is accomplished by inserting a high-band filter in the signal's path.

The electrical components of the MAGIC I setup are shown in figure (6). After the PMT the signal is split into two branches. An unmodified part goes to the so-called slow branch, where it is digitized at 1 Hz. The other branch passes through a capacitor that filters the slow component and is transmitted through an optical fiber. When operating in interferometry mode the signal at the end of the fiber is continuously digitized at a very high frequency, 500 MHz. As the amount of data generated in this mode is huge it can´t be stored, it is directly processed by GPUs and only some characteristics of the data are kept. In the case of interferometry, the correlations between different channels are recorded; in the case of Fast Photometry, the mean, max, min, and RMS (Root Mean Square) of the data are computed over a large number of samples.

The number of samples selected by default by the system is 2^{18} (262 144 samples). As samples are spaced 2 nanoseconds, about 0.5 milliseconds are used to estimate each value. The number is quite small, and we have further averaged the results to reduce the fluctuations, but it is important to note that for strong signals where fluctuations would have a lesser influence, this 0.5 ms time resolution would be available.

The idea to overcome the effect of the low-frequency filters present in the signal path is to use the RMS of the samples instead of the mean. Since the signal in any short time interval is initially a small number of photons that reach the PMT its distribution must be Poissonian. Due to the properties of this distribution, the RMS must be equal to the square root of the mean. Computing the RMS, we have access to the mean of the signal even if it is filtered electrically. If this is to be a good approximation, the rest of the fluctuations (electronic noise, tracking oscillations, atmospheric effects) must be smaller than the Poissonian ones, or at least, vary on different time scales so we can filter them out.

In the following graph, figure 15 we can observe the RMS and its square along with the mean of the data, all of them versus time, averaged over 20 samples. First of all let´s note that while the square of the RMS would be the right variable to use in the case of a perfect Poissonian distribution, the RMS itself is very similar, probably due to the presence of other sources of noise and to the small variations of the signal, of the order of 1-3%. Therefore in this work, we have used RMS instead of RMS^2. It can also be seen that the mean of the samples oscillates rapidly, making it impossible to tell apart the event. This confirms the effects of the already-mentioned filtering. Finally, it can be seen that there is a fast noise component that makes the signal a sort of thick line. To eliminate it in this work, we have averaged over 100 samples and computed the error bars as the expected uncertainty of the mean.

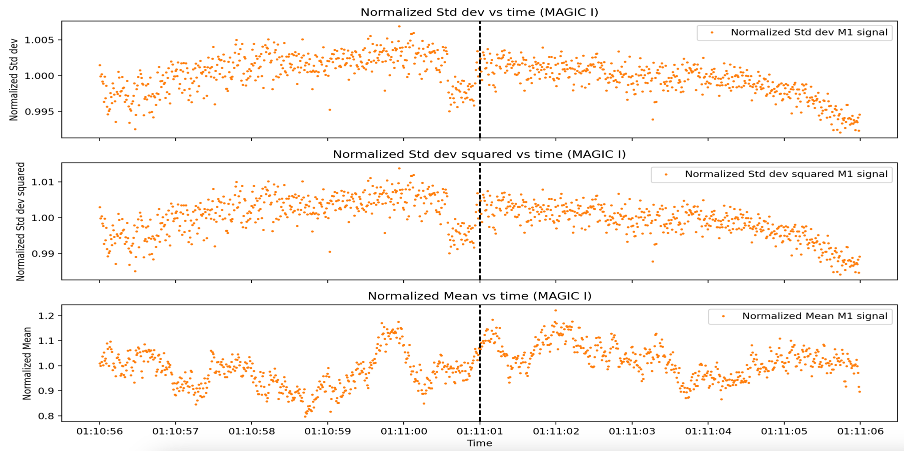


Figure 15: In descending order: RMS, RMS^2 and mean; versus time. The dotted line represents the actual time of occultation.

Another important point to consider is the slow variations in the graph, or equivalently, the low-frequency noise. They are probably due to variations in the PMT gain, atmospheric effects, and instabilities in telescope tracking. Their effect depends on the signal we want to observe. In the case of our occultation, although the total fluctuation in the signal seen in the 10 seconds shown is larger than the drop in intensity during the 0.5 seconds of the occultation, it could be observed because of its short duration. A measure of their importance can be the scale of the fluctuations in the length of time considered. The signal varies more on long-time scales than short ones; thus, we can more easily detect short occultations than long ones. To get an idea of how significant this effect is, we proceed to create a histogram of the signal on two-time scales: 10 seconds and 2 minutes. Estimating the fluctuations by the distribution's Full Width Half Maximum (FWHM), it can be seen that it is around 1% on the short time scale and around 2-3% on the long one. We conclude that signals of the order of 1% can likely be observed on short time scales while around 3% would be required for longer lengths. It is a relatively good precision, compared with the results of the previous section, this translates in that occultations involving stars of magnitude around 11 can be observed regardless of their length. A systematic study would be needed. As a caveat, the occultation in the 10-second graph may have influenced the results, increasing the RMS, but its effect is small as its length is short.

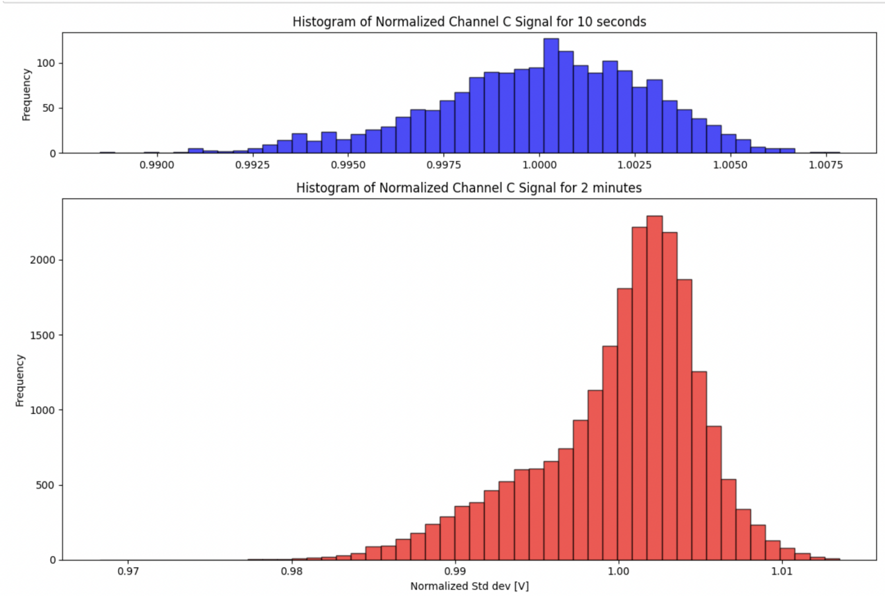


Figure 16: Histograms of the signal in the observations of FE79 for two different periods: upper one for 10 seconds around the occultation, lower one for 2 minutes around the occultation. Both histograms are normalized.

5 Discussion of the results and conclusion

We have had the opportunity to test MAGIC's *fast photometry* mode for the first time to observe occultations, using predictions from Occult Watcher and proposing its observation. Thus, two occultations may have been detected, one positive and the other just possible, demonstrating that it is feasible and opening the path for further work in this field.

We have commented on the advantages and disadvantages of using the MAGIC telescopes for this purpose. The limited sensitivity of its components was partially compensated for by its very good temporal resolution, which allowed us to measure the positive occultation precisely.

Being able to observe an occultation has been proven to depend on many factors. Out of the 13 occultations were proposed, but only five were observed; one was successful, and another one had some chance of being positive. If we also consider the large number of predictions generated by Occult Watcher, throughout the study period, we can conclude that observing occultations of stars by asteroids with MAGIC is difficult and success unlikely.

Finally, we conclude that photometric observations with MAGIC are possible but are limited by the large pixel size and relative signal instability. Both effects are briefly analyzed in the text.

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