Chapter

Lunar Occultation

Abdulrahman Malawi

Abstract

A detailed explanation of the reduction method used to determine the angular diameters of the stars occulted by the dark limb of the Moon is presented.

Keywords: Moon, ephemeris time, occultation, stars, angular diameters

1. Introduction

The disappearance of a star behind the dark limb of the Moon yields very useful information about the star and the lunar surface near that point. This phenomenon is known as lunar occultation. It is in fact part of a very well-known astronomical event—occultation—the disappearance of a nearby celestial object behind another one. The disappearance of the sun behind the Moon, total solar eclipse, the disappearance of planets behind the Moon, or the disappearance of stars behind planets or asteroids are a few examples of this scientifically important phenomenon.

Many scientists have been studying occultation for more than a century (e.g., [1–5]). During the occultation the intensity of the occulted star drops to zero in a very short time. Scientists noticed that the time of the disappearance of the occulted star could be used to determine the diameter of the star. For example, an occulted star with an angular diameter of 0.001 arcsec disappears in 1/50 s, which could easily be measured with photographic recording methods available at that time. Occultation investigations then followed consequently, and a remarkable observation was reported by [6] who used a spinning photographic plate to detect an occultation of Regulus. Diffraction fringes were observed, from which he deduced a diameter of 0.0018 arcsec for the star. This value was in substantial agreement with a later value of 0.0013 arcsec measured by utilizing the intensity interferometer at Narrabri [7]. Scientists in South Africa [8–10] used photographical techniques to make sequence of occultation observations of the red supergiant star Antares, from which they determined the angular diameter of the star. The diameter of μ Geminorum was also determined [11]. The values of the angular diameters of these two stars, which were not affected by the diffraction effects, were found to be 0.040 and 0.023 arcsec, respectively. Ref. [12] also discussed the effect of lunar surface irregularities in the case of stars with large angular diameters. Modern powerful computers and state-of-the-art CCD cameras, along with readily available fast-speed direct digital data recorders, made it very easy for occultation observations to be carried out and for precise models to be constructed.

Lunar occultation observation is the most powerful technique used, to date, for high angular resolution measurements of stars, which made it so important and increases its growth of interest [13–17], adding to the wide range results that can be obtained from analyzing the data. Starting up a lunar occultation observation program is cost-effective (inexpensive) and can be achieved with small- as well as large-sized telescopes. Therefore, such program should be considered by medium-sized observatories, even amateur individual observers, making it possible to achieve millisecond resolutions with 1–2 class telescopes fitted with fast photometers [18].

The measurement of stellar diameters is not the only application of this technique and, indeed, may not even be the most fruitful one. Occultation timings are used by the Nautical Almanac offices for the determination of ephemeris time and to improve the theory of the Moon, while the incidental discovery of double stars has been frequent but almost totally unexploited. The event creates a good ground base for an amateur astronomer to do something meaningful in their lives.

2. Theory of occultation and the reduction method

The increased efforts made to time occultation observations, very accurately, resulted in obtaining a detailed information about the limb profile of the Moon. Thus, several observatories established and run observing and analyzing programs. The observed light curves are used to determine the stellar angular diameters, as well as discover double and multiple star systems and map the lunar limb irregularities (see [19] and references therein).

As the Moon precedes between a point on the Earth's surface and the above background stars, it casts down a shadow that moves at a high speed (**Figure 1**).

If the star is observed by a telescope during the shadow passage, the intensity of the starlight would be seen to fluctuate as a result of the movement of the shadow across the aperture of the telescope and ultimately disappears when the lunar shadow becomes total.

The record of these fluctuations constitutes an occultation observation. The intensity pattern F(w) of a monochromatic point source obscured by a straight sharp edge can very well be described in terms of Fresnel integrals ([11]) as

$$F(w) = I_{\circ}\frac{1}{2}\left[\left(\frac{1}{2} + C(w)\right)^2 + \left(\frac{1}{2} + S(w)\right)^2\right] \tag{1}$$

where C(w) and S(w) are the Fresnel integrals and they are written as

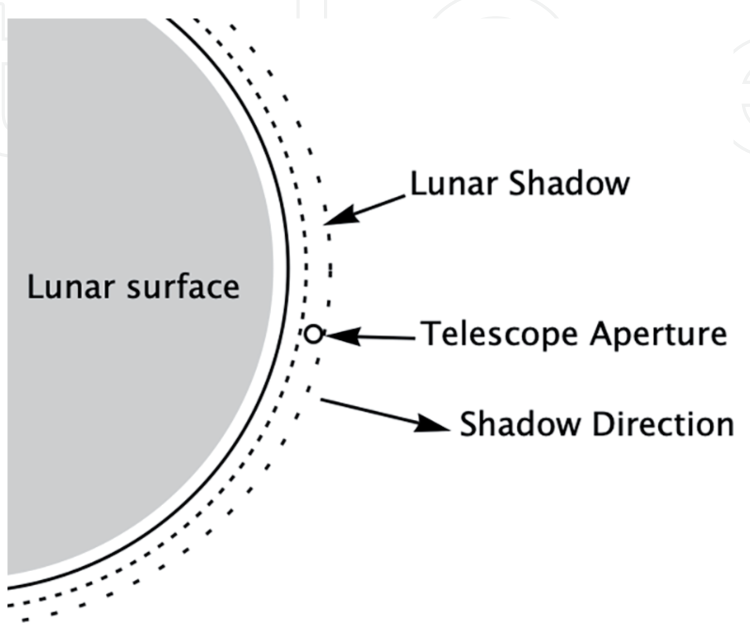

Figure 1.
Diffraction fringes from the lunar limb cross the telescope objective.

$$C(w) = \int_0^w \cos\left(\frac{\pi}{2}t^2\right) dt \tag{2}$$

$$S(w) = \int_0^w \sin\left(\frac{\pi}{2}t^2\right) dt \tag{3}$$

where

$$w = x\left(\frac{2}{\lambda D}\right)$$

Hence the observed light curve is

$$f(x, \lambda) = F(w) \tag{4}$$

where x is the distance in meters from the telescope to the edge of the lunar shadow, λ is a single wavelength, and D is the distance of the Moon from the observer. **Figure 2** shows a monochrome (500 nm) Fresnel diffraction light curve, while **Figure 3** shows the effect of a finite band pass (380–420 nm) on the light curve.

Practically, the diffraction pattern, defined by Eq. (4), is altered by various factors related to the wavelength dependence (detector response, filter band pass, and source dependencies), telescope objective, source size, and the like, as shown in Eq. (5):

$$F_j = E_\circ + I_\circ \iint S(\lambda)\, f(x, \lambda, \phi)\, D(x)\, \phi(R)\, d\lambda\, dx \tag{5}$$

$S(\lambda)$ comprises the sensitivity function of the detector and the filter, as well as the spectral distribution of the star. It is very important to notice that large telescopes can cause blurring of the fringe patterns, which results in loss of some information, but this is recompensed by the improvement of the S/N ration. Since both finite band width and telescope aperture result in blurring the finer fringes of the light curve, both of them limit the effective spatial resolution in a similar, though not identical, manner. For example, a 2-meter telescope limits resolution to about 0.001 arcsec, while a bandwidth of about 200A (centered at 4000 A) has about the same effect.

The finite disk of the star (**Figure 4**) has the same effect as the telescope aperture, as shown in **Figure 5**. An observer at the center of the Earth sees the Moon moves across stellar background at a rate of about 0.5 arcsec per second, i.e., a fringe passing rate of 0.9 m/s for a star occulted at the leading side of the Moon.

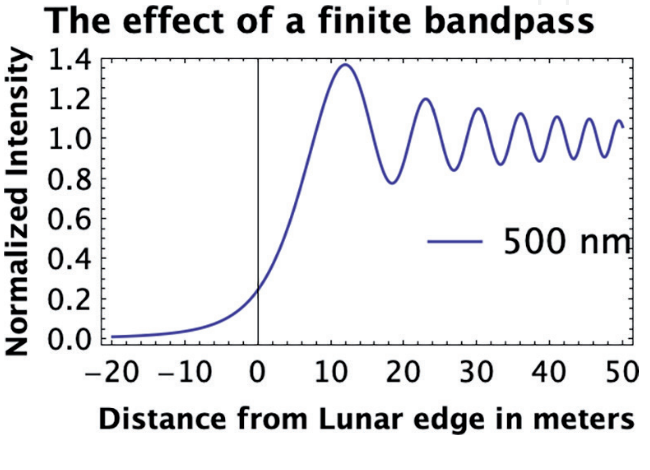

Figure 2.
Monochrome (500 nm) Fresnel diffraction light curve.

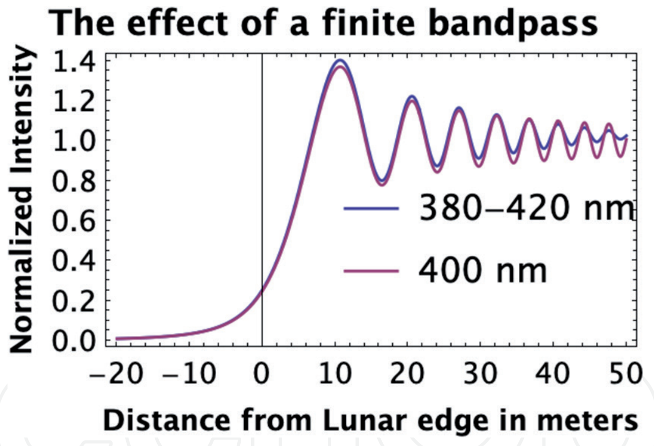

Figure 3.
The effect of a finite bandpass (380-420 nm) on the fine fringes of light curve.

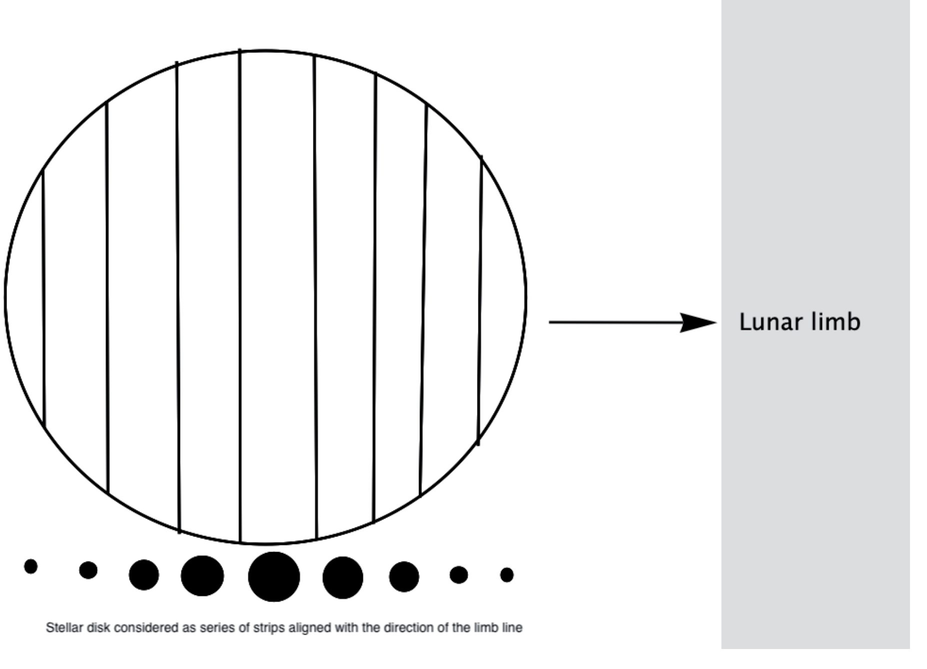

Figure 4.
Stellar disk considered as series of strips aligned with the direction of the limb line.

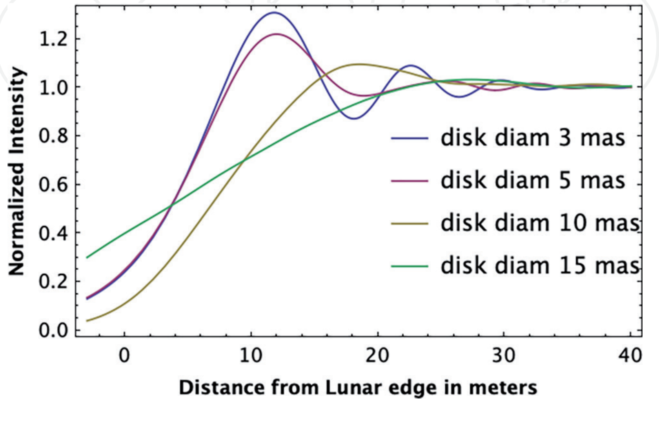

Figure 5.
The effect of uniform circular disk on fringe patterns.

The time scale of the event has been shown to be altered by the angle between the contact point of the occulted star and the motion vector of the Moon ([20]); therefore, scientists proposed that the most appropriate occultation events would be

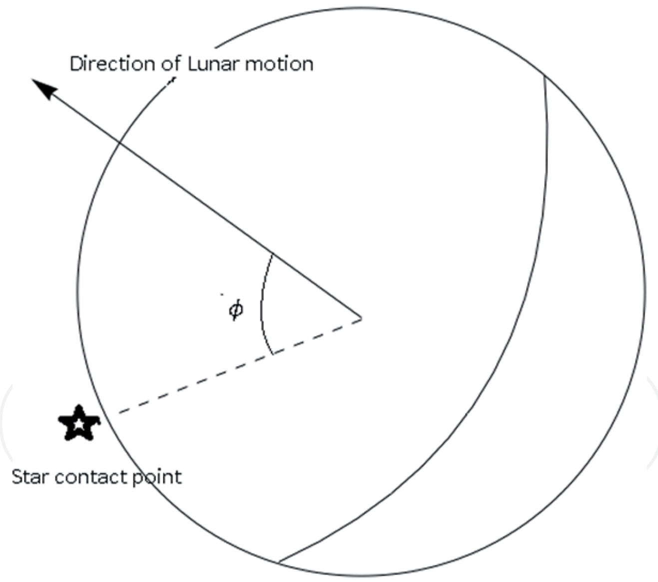

Figure 6.
Occultation time scale is extended by the factor of sec ϕ.

those grazing the edge of the Moon. The effective fringe passage time, as seen from the Earth, is changed by a factor $sec(\phi)$, where ϕ is the angle between the direction of lunar motion and lunar limb at contact point (see **Figure 6**).

The abovementioned effect can improve the quality of an occultation trace. An additional effect on the time scale should also be accounted for. For example, since the Earth rotates in the same direction of the lunar motion, the rate of the lunar motion is decreased due to change in parallax. An equatorial observer, observing when the Moon is on the meridian, near the zenith, will see 50% reduction in the lunar rate. This effect varies as latitude is increased and as the Moon approaches the horizon.

The time scale of fringe passage is also affected by the slope of the lunar surface; therefore, the difference between the obtained parameter of the velocity and the computed velocity is supposed to be caused by the slope of the lunar surface, and one can, in this case, determine its value.

3. Data fitting

The most popular method of analyzing occultation data is the least square method, first introduced by [21]. The Levenberg-Marquardt method of nonlinear fitting subroutine ([22]) fits the model light curve to the observed data of the occulted star. Most of the computed time is taken by Fresnel integrals C(w) and S(w). Therefore, one must use the fastest approximations. Tchebycheff approximations [23] found in [24] is used [25]. It takes the form

$$C(w) = \left(\frac{1}{2} + a(w)\, sin\left(\frac{\pi}{2}w^2\right) - b(w)\, cos\left(\frac{\pi}{2}w^2\right)\right) sign(w) \tag{6}$$

$$S(w) = \left(\frac{1}{2} - a(w)\, con\left(\frac{\pi}{2}w^2\right) - b(w)\, sin\left(\frac{\pi}{2}w^2\right)\right) sign(w) \tag{7}$$

with

$$a(w) = \frac{1 + 0.926|w|}{2 + 1.792|w| + 3.104w^2} \tag{8}$$

$$b(w) = \frac{1}{2 + 40124|w| + 3.492w^2 + 6.670|w|} \tag{9}$$

The program, simultaneously, adjusts five free parameters (the velocity of the shadow A1, the occultation occurrence time A2, the angular diameter of the star A3, the amplitude of the observed light curve at continuum A4, and background level of observed light curve A5) until best fit is obtained. An initial estimate of these parameters must be fed to the computer, adding to the values of another three fixed parameters, representing the observed wavelength, filter bandwidth A6, the Earth-Moon distance A7, and the contact point of the occulted star at the lunar limb A8. The adjustment is carried out by the least square method, mentioned above. The relation between the independent parameters and the values of the Fj is nonlinear; therefore, the program linearizes the equation and iterates until a convincing solution (small χ^2 value) is obtained. The fitting parameters must be provided with expressions for the derivatives of the adjusted parameters with respect to the model function as follows:

$$\frac{dF_j}{dA_1}, \frac{dF_j}{dA_2}, \frac{dF_j}{dA_3}, \frac{dF_j}{dA_4}, \frac{dF_j}{dA_5} \tag{10}$$

When the best fit is found (with minimum value), the program displays the final values of the adjusted parameters, which are supposed to represent the physical states of the occulted star.

4. Estimating the error of the angular diameter measurement caused by scintillation

In order to check our procedure, and to estimate the effects of noise on the calculated parameters, we produce several artificial light curves that represent stars with uniform disks and then modify each curve by adding scintillation noise to it.

The simulated occultation light curves were generated by arbitrarily choosing a portion of each scintillation measurement of 120 data points' length, normalizing it to one, and then adding it to the same length and time resolution of the artificial Fresnel patterns, to give a light curve exactly the same as the light curve resulting from a real occultation. See [25] for more details.

5. Results

Timing and observing lunar occultation events have very important scientific results. For example, grazing occultation observation can be used to gain valuable information about the limb profile of the Moon as well as the occulted star. By combining modern observing equipment and precise time-keeping devices, one can obtain very precise measurements. **Figure 7** illustrates the event of a single grazing occultation, where eight events were observed. The first disappearance is shown on the left and the last reappearance on the right. The carvery line is the lunar terrain.

Figure 8 (taken from [26]) shows a nearly grazing disappearance occultation observation of the 3.1 mag, A5 spectral-type star 9β Capricorn, SAO 163481, also known as Dabih. This is the main star in a multiple star system. The observation was carried out on 22 Oct. 1993, with a fast photometer, at a sampling rate of 1 mas per data point. Fine details of the fringe pattern of the light curve are perturbed and deformed by scintillation noise, which is the main source of noise,

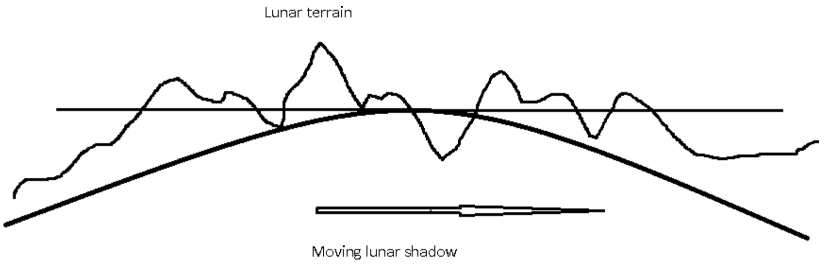

Figure 7.
Illustration of the event of a single grazing lunar occultation.

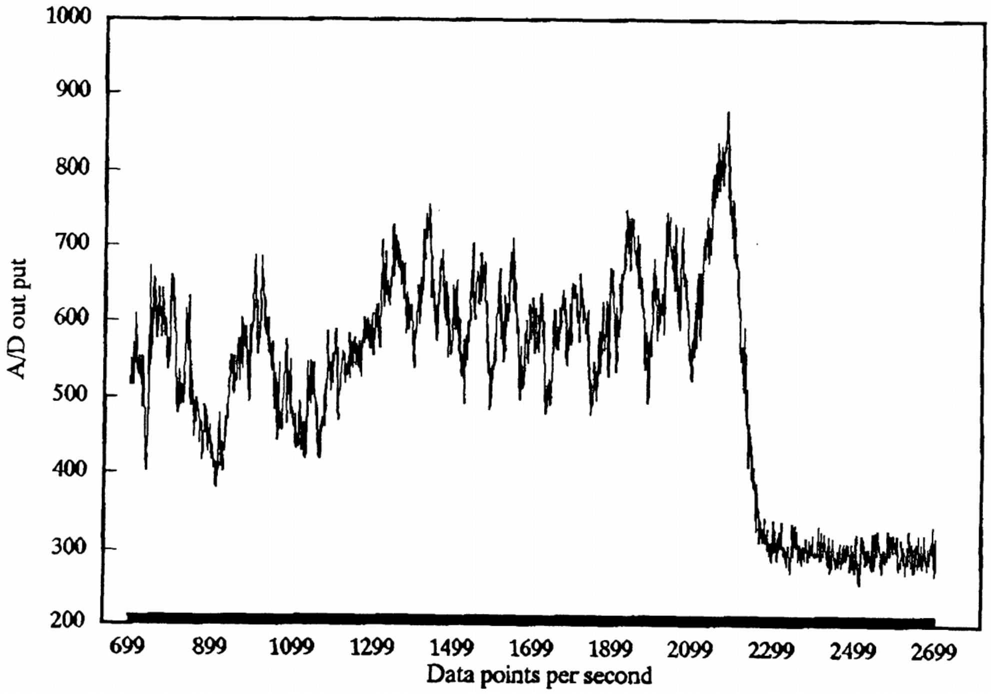

Figure 8.
Light curve of a near grazing lunar occultation of the star 9 β Capricorn, image taken from Malawi et al., 1994.

especially for observations that are carried out at large zenith distance. Other effects, such as irregularities of the lunar limb, and the time delay of the fringe passage caused by nearly grazing occultation can also be seen in the resulting light curve. The best way to minimize the scintillation effects as well as effect of irregularities in the lunar limb is to have multiple observations of the same event whenever possible. If a team of many observers, together, observed the same event, from different locations, perpendicular to the occultation path, they can construct a very accurate profile of the lunar terrain, in the northern and southern pole areas of the Moon.

An example that shows ability of the model-generated curve to fit the observed data is shown in **Figure 9**, where the dots represent the observed data points, whereas the solid line shows the best fit model. The occulted star is 6.69 mag, A7 spectrum (SAO 97647) that was observed on 6 May 1995. The calculated angular diameter is 2.056 ± 0.69 mas. **Table 1** shows the calculated values of the five variable parameters. The estimated angular diagram of the star is 0.0002, "five folds less than the limited angular resolution of the system which is set to be 0.001."

Scintillation effects on the light curve and the smearing of the fine fringe pattern are clearly seen in **Figure 9**. An additional cause of such distortion is the finite band width of the filter used in the observation.

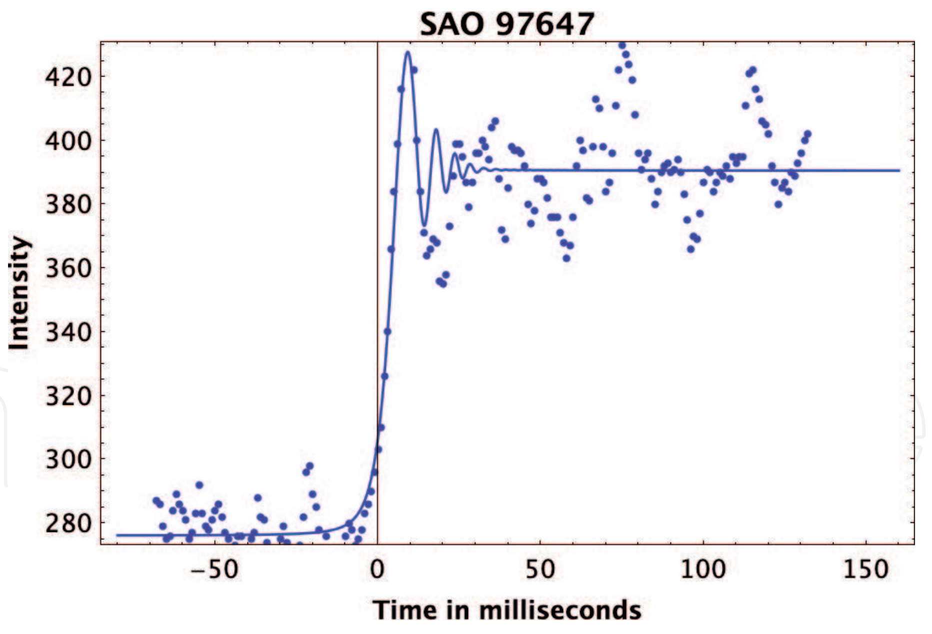

Figure 9.
Observed light curve of the star SAO 97647 (dots) shown along with fitted model (solid line).

Parameter	Estimated	Standard error	Confidence interval
A1	3.58359	0.134282	{3.31876, 3.84841}
A2	0.392329	0.409685	{−0.415628, 1.20029}
A3	2.05561	0.692487	{0.689925, 3.42129}
A4	114.438	1.93875	{110.615, 118.262}
A5	276.119	1.59709	{272.969, 279.268}

Table 1.
The calculated values of the variable parameters.

6. Conclusions

Lunar occultation event offers us a very good chance to study the nature of one or both objects and pave the way for continuing research. For example, grazing occultation observation can be used to gain valuable information about the limb profile of the Moon as well as the occulted star. Observing lunar occultations from different locations is very important, to benefit from the different entering angles of the occulted stars, which helps improve the timing as well as the information about the lunar surface. Although the Japanese Kaguya mission launched in 2007 and the NASA Lunar Reconnaissance Orbiter mission (LRO) in 2009 mapped the lunar surface with an accuracy of 200 down to 5 m, grazing occultations still play an important role in the precision improvement of the lunar terrain features.

Occultation observations, usually, do not require large telescopes. Even telescopes as small as 6 cm refractor or an 11 cm reflector are enough to be used for most occultation events. Since graze paths not often pass over established observatories, amateur astronomers use portable observing equipment and travel to sites along the shadow path limits. The Universal Time Coordinated (UTC) of each event is recorded as accurately as possible, and the observed data is reported to the International Occultation Timing Association (IOTA). By doing so, amateur astronomers can contribute to science. Amateur astronomers can, also, play an important role by discovering unknown double and multiple star systems and/or can investigate them closely through their occultations by the Moon. If timing is made with high resolution, outcome is of high professional interest, to learn more about these systems and to measure stellar diameters. Reductions of grazing occultations also help discover errors in the stellar proper motions as published in the Hipparcos catalog, as well as reveal the rotational error of the Hipparcos reference frame. More details about timing, video or photometric recording, or analyzing lunar occultation observations can be obtained by visiting the web site of the IOTA.

Author details

Abdulrahman Malawi
Kin AbdulAziz University, Jeddah, Saudi Arabia

*Address all correspondence to: amalawi@kau.edu

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