# Image Analysis of the 2012 Pluto (Near) Occultation

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**ABSTRACT**

Imagery was gathered at the AMOS observatory on the 3.6-meter telescope for the expected occultation of a star by the dwarf planet, Pluto, on 29 June 2012. The imagery was taken at 5 Hz for 40 minutes before and after the expected time of occultation. The initial analysis of the photometry indicated that Pluto did not occult the star. This conclusion could not be determined from a simple visual inspection of the imagery. Understanding why and by how much Pluto missed occulting the star can aid in predicting future occultations.

To analyze the imagery, a least squares method was developed to measure the closest approach, in arc seconds. The method is based on averaging the modulus squared of the Fourier transform of the imagery. This is similar to Labeyrie's technique in speckle interferometry. From this method, fringes were detected and measured as a function of time over the period before and after the near occultation.

The analysis showed that Pluto missed the star by 0.135 arcsec with an accuracy of 0.003 arcsec. The use of over 24,000 image frames leads to this high level of precision. In addition, Labeyrie's technique applied to the images of Pluto by itself, shows that Pluto and its moon, Charon, were oriented perpendicularly to the direction of travel, making it even less likely that Pluto would overlap with the star. The methods developed to conduct this analysis and the conclusions reached are described in this paper.

## 1. INTRODUCTION

An occultation of a dim star by Pluto, that would be visible in Hawai'i, was predicted for 29 June 2012, at 11:57:49 UTC. That corresponded to two o'clock in the morning, local time, when the shadow was predicted to cross Hawai'i. We, at the AMOS (Air Force Maui Optical & Supercomputing) site, were asked by Eliot Young of the Southwest Research Institute of Boulder, Colorado, if we would be interested in participating on a collection of photometric data on this occultation. We agreed and began making arrangements to observe Pluto on the morning of 29 June. Eliot Young made additional arrangements with other observers around the Sate of Hawai'i to make observations with small aperture telescopes.

The goal of recording the shadow, as it travels over the earth, is to measure the dip in the amount of light received from Pluto and the star as Pluto goes in between the star and the Earth. As Pluto blocks the light of the star, any atmosphere of Pluto will partially deflect the light, softening the edge of the dip. A careful measurement of the edges of the dip in the light curve enables the density of the atmosphere to be studied [1].

The photometric analysis of the data showed that, unfortunately, the shadow of Pluto did not cross the State of Hawai'i. In other words, there was no dip in the photometric curve of the occultation. Eliot Young warned us before the arrangements were made that it was not certain that the shadow would cross our location, but that there was a high likelihood that we would see it. The photometry said that we did not.

From our viewpoint, the data had value in addition to the possibility of investigating Pluto's atmosphere. The sequence of images represents a very close pass of two objects of similar brightness. The star, designated P20120629, is about 14$^{th}$ visual magnitude, which is comparable to the brightness of Pluto. The expected angular separation of Pluto and the star, as well as the actual separation, would be smaller than the angular width of the atmospheric seeing from Earth (one arcsec). That means that the closest approach of Pluto and the star could not be measured directly. An indirect method to deduce the angular separation of the closest approach was developed to analyze this data. The method resulted in a measurement that has a higher angular precision than the diffraction limit of the telescope taking the data. In addition to measuring the value of the closest approach, we were able to show why the occultation did not occur, even though the orbital calculations, ahead of time, predicted that it would.

## 2. DATA COLLECTION

The image data of Pluto and the star P20120629 was taken on the 3.6-meter AEOS telescope, which is shown in Fig. 1. The camera was an Andor iXon 897, running at 5 Hz in EMCCD, high-gain mode. The filter passed light longer than 700 nm, but the sensor sensitivity ends around 1,000 nm. The field-of-view of the telescope was 10 arcsec.

Fig. 1. The 3.6-meter Advanced Electro-Optics System (AEOS) telescope at the AMOS observatory.

The data was gathered from 50 minutes before the occultation through to 50 minutes after the occultation. At 5 frames/sec, a total of 30,000 frames were collected. No adaptive optics loop was engaged, so all objects were blurred by the atmospheric seeing disk of approximately 1 arcsec. In addition, each frame was subjected to a random tip-tilt of approximately another arc second.

An example frame is shown in Fig.2a. Within the field-of-view was Pluto, the occultation star and a much dimmer neighboring star. The image in Fig. 2a was taken about 25 minutes before occultation. Both Pluto and the star are about 1 arc sec in diameter due to the atmospheric seeing. Pluto is about $14^{th}$ visual magnitude and the occultation star was slightly brighter. The noise in the image is photon noise, due to the short exposure and the dimness of the objects.

A composite image of the complete pass is shown in Fig 2b. In this image, Pluto can be seen as it apparently moves in front the P20120629. The occultation star appears brighter in the composite than in the individual frame because of the overlap of 5 images in the creation of the composite image. Each image in Fig. 2 consists of an array of 512 x 512 pixels with 14 bits dynamic range.

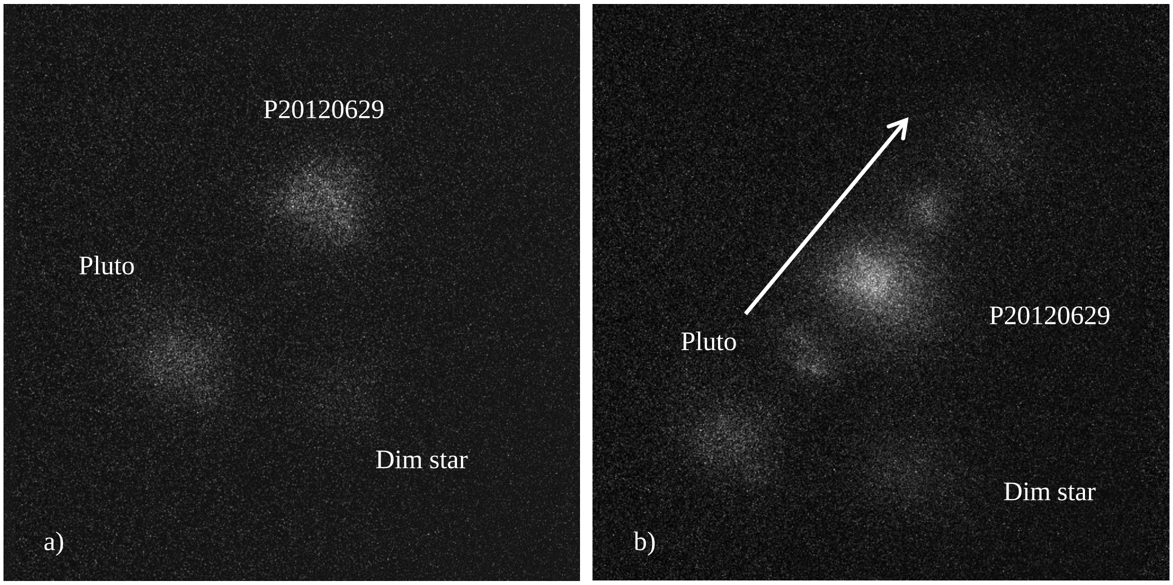

Fig. 2. The path of Pluto during the occultation of P20120629, a) single frame, b) composite image.

## 3. SPECKLE INTERFEROMETRY

In 1970, Antoine Labeyrie [2] developed a technique to detect double stars that are closer than the width of the atmospheric seeing disk. This method is routinely used today to measure the separation of double or binary stars that are closer together than an angular separation of 1 arc second. The method consists of computing the Fourier Transform of each image frame, taking the square modulus of each Fourier Transform, and adding many such transforms together. The resultant sum contains straight line “cosine” fringes that indicate the separation and orientation of the two objects.

This method is based on the concept that two objects that are very close together, when viewed through the atmosphere, are blurred by the exact same atmospheric point spread function. If both of the objects are unresolved, then the image consists of the exact same atmospheric point spread function placed at two locations in the frame and summed together. Although Labeyrie’s method was devised for objects that are closer together than the width of the atmospheric point spread function, it works for objects that are farther apart, as long as the two objects are in the same isoplanatic patch, i.e. the same atmospheric point spread function is applied to both objects.

If the atmospheric point spread function is p(x, y), then the image of the two objects is given by:

$$i(x,y) = p(x - \Delta x/2, y - \Delta y/2) + ap(x + \Delta x/2, y + \Delta y/2), \tag{1}$$

where, *a*, is the ratio of the brightness of the two objects, and the separation distance between the two objects, *d*, is given by:

$$d = \sqrt{\Delta x^2 + \Delta y^2}\ . \tag{2}$$

The Fourier Transform of the image, *I*, converts the translation shifts, $\Delta x$ and $\Delta y$, into linear phase factors. Capital letters are used to represent the Fourier Transform of the corresponding quantity.

$$I(u,v) = P(u,v)\left(e^{-i(\Delta xu + \Delta yv)/2} + ae^{i(\Delta xu + \Delta yv)/2}\right) \tag{3}$$

The square modulus of the Fourier Transform of the image, *I*, becomes:

$$\left|I(u,v)\right|^2 = \left|P(u,v)\right|^2\left[(1-a)^2 + 4a\cos^2(\Delta xu/2 + \Delta yv/2)\right] \tag{4}$$

If the two objects are the same brightness, i.e. $a = 1$, then the square modulus is:

$$\left|I(u,v)\right|^2 = \left|P(u,v)\right|^2 4a\cos^2(\Delta xu/2 + \Delta yv/2) \tag{5}$$

This equation shows that the square modulus of the Fourier Transform is the square modulus of the Fourier Transform of the point spread function, multiplied by a set of cosine squared fringes, whose separation and orientation depend inversely on the separations, $\Delta x$ and $\Delta y$, in the image. Any arbitrary random shift, due to the atmospheric turbulence, is removed in the squaring process and does not enter into the measurement process. Fig. 3a shows the square modulus of the Fourier Transform of the one image frame from Fig. 2a. The right-hand side of Fig. 3 is the average of 1,000 Fourier Transforms, all similar to Fig. 3a. The summation results in a cleaner set of fringes. Note that the lines of the fringes point in the perpendicular direction to the object separation.

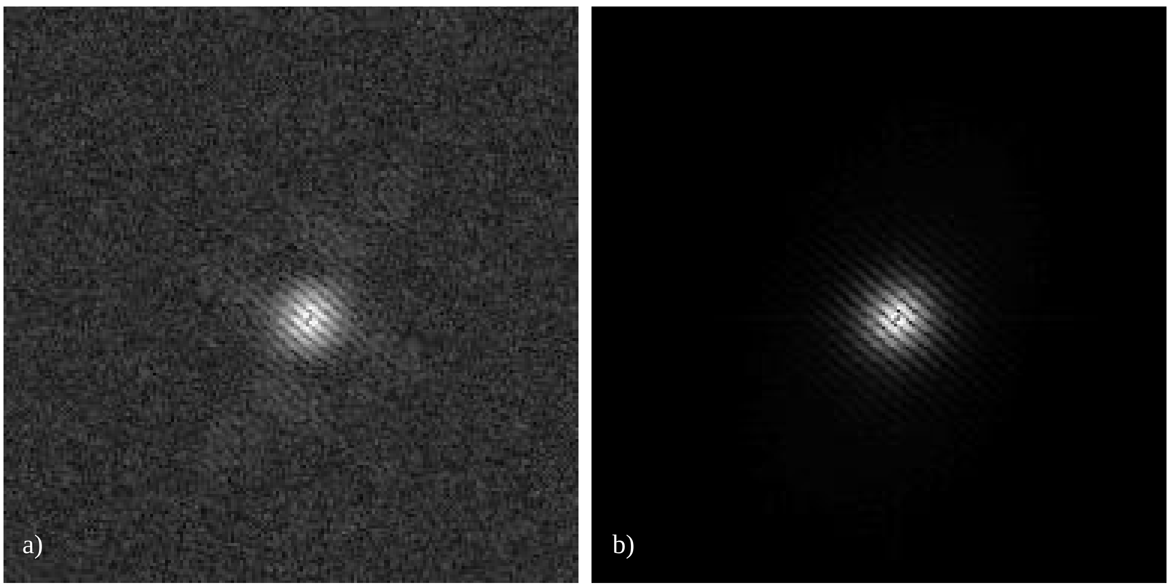


Fig. 3. The square modulus of the Fourier Transform of image frames, a) single frame, b) sum of 1,000 frames.

## 4. CLOSEST APPROACH ANALYSIS

Since the fringes will indicate two objects close together within the atmospheric seeing disk, why not wait until near the closest approach and check the fringes to find the ones that are farthest apart, corresponding to the closest approach? There are two reasons why this does not work. The fringes at closest approach are the broadest fringes and they may not be measureable if the frequency spectrum of the atmospheric turbulence does not extend out to the diffraction limit. Secondly, the exact moment of the closest approach is not known, so when to measure the fringes is uncertain.

As a result, a new method was needed to determine the value and the time of the closest approach. This method is based on analyzing the whole sequence of image frames. Fig. 4 shows a schematic diagram of the pass of Pluto by the occultation star. The point of closest approach occurs at time, $t_0$, and is equal to, $h$, the perpendicular distance between the star and the path of Pluto. At any given time, $t$, a right triangle can be drawn with its vertices at Pluto, the occultation star and the point of closest approach. If Pluto is moving at an angular velocity, $v$, then the distance from Pluto to the point of closest approach, along the path of Pluto, is given by, $v(t-t_0)$. Since this triangle is a right triangle, the Pythagorean Theorem defines a simple relationship between the three sides of the triangle.

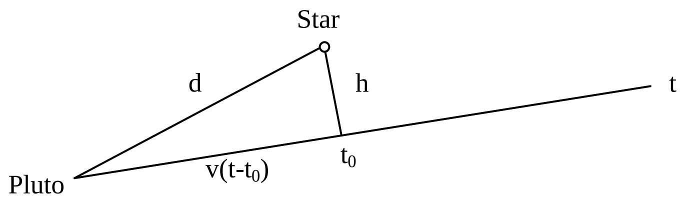


Fig. 4. The right triangle that defines the positions of Pluto, the occultation star and the point of closest approach.

The Pythagorean Theorem says that the distance of closest approach is given by:

$$d^2 = h^2 + v^2 (t - t_0)^2 \tag{6}$$

The distance, *d*, is just the distance between the two objects, as a function of time, and is determined by measuring and inverting the fringe separation for each frame in the sequence. The time, *t*, of each frame is known. The other three variables in Eq. 6, *h*, the distance of closest approach, $t_0$, the time of closest approach, and, *v*, the relative velocity of Pluto along the path, are unknown.

If the quantity $d^2$, measured for each frame, is plotted again the time, *t*, then it should form a parabola. By fitting a minimum least-squares parabola to the measured data, the three unknown parameters can be estimated. Fig. 5 shows the measured distance plotted against time, together with the fitted least square parabola.

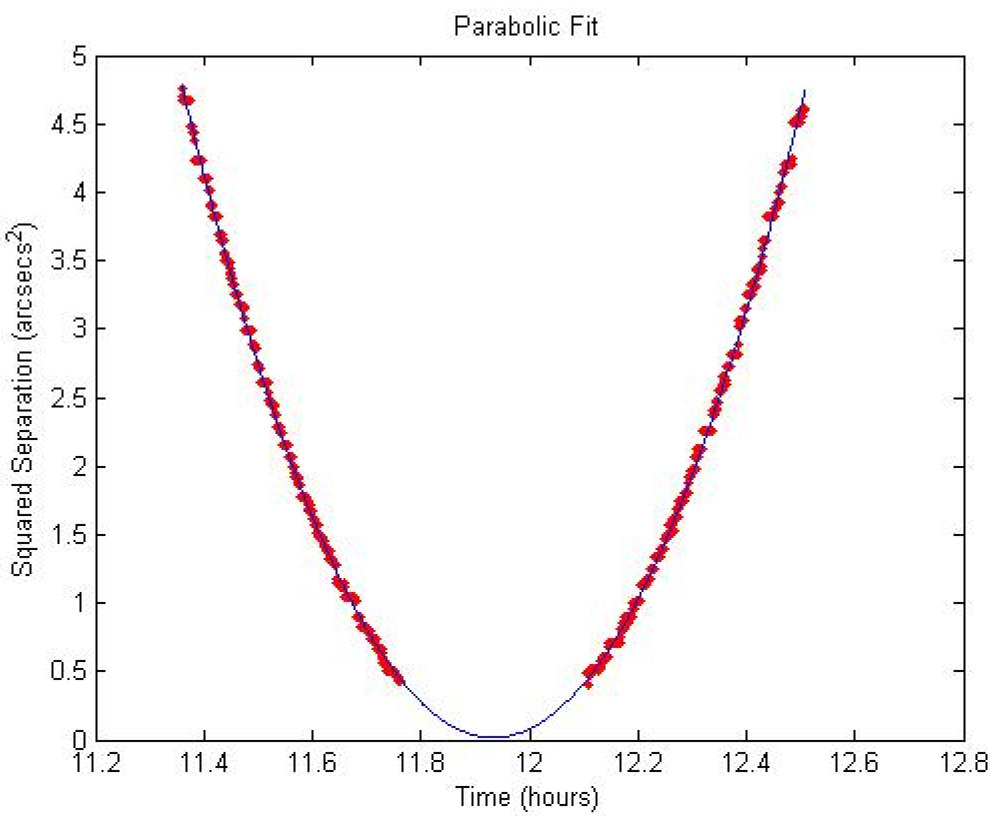


Fig. 5. The data points are plotted in red. The blue line is the least squares fitted parabola.

The fit of the parabola to the measured data is quite good with a high degree of accuracy. From the graph in Fig. 5, it can be seen that the parabola does not quite touch the origin at the minimum point. The additive constant that this minimum value corresponds to, by Eq. 6, can be seen to be equal to $h^2$, the square of the distance of closest approach.

The confidence levels in the estimations of the parameters were calculated using the Monte Carlo Simulation method [3]. In this method, random draws are made from the data set of 28,000 measurements, and a series of 10,000 estimations were computed. The uncertainties of the estimations are computed from the Monte Carlo set of estimations.

Using the plate scale of 0.0185 ± 0.0001 arcsec/pixel for this sensor, the estimations of the three unknown parameters and their confidence levels were determined to be:

$$\begin{aligned} v &= 3.79 \pm 0.02 \text{ arcsec/hr} \\ t_0 &= 42965 \text{ seconds} \pm 0.14 \text{ seconds} \\ h &= 0.135 \pm 0.003 \text{ arcsec} \end{aligned} \tag{7}$$

The uncertainty in the estimate of the time of closest approach is slightly less than the time between exposures, which is reasonable. The estimate of a relative velocity of approximately 4 arcsec/hr is reasonable considering that the Pluto and the star stayed within the 10 arcsec field-of-view for two hours.

The really amazing figure in these estimations is the estimate of the distance of closest approach, *h*. The value of 0.135 arcsec is well within the atmospheric seeing disk, which is about 1 arcsec wide. What is very amazing is the confidence level of ±0.003 arcsec, since the best resolution of the 3.6-meter telescope at these wavelengths is 0.06 arcsecs. In other words, the accuracy of this estimate is 20 times better than the highest resolution image that can be gathered from this telescope. The reason for the extreme high accuracy of this estimation is that it is made from 28,000 images and it is based on a model of linear motion of the two objects.

## 5. PLUTO/CHARON ORIENTATION

The next question to ask is: if Pluto passed within 0.135 arcsecs of the occultation star, why was there no change in the photometry, i.e. why did Pluto not block any of the light of the star?

To answer this question, we need to learn a little more about Pluto, or perhaps, the Pluto system, i.e. Pluto and its moons. Pluto is estimated to have a diameter of 1306 km, or at its current distance from the Sun, an angular extent of about 0.1 arcsec. This is approximately the angular distance that separated Pluto and the Star. Since the distance of closest approach was more slightly more than the diameter, and therefore, more than twice the radius, it is clear that Pluto would not block any of the light of the star.

How could the prediction of the location of Pluto be so far different from the prediction? To understand that, it is necessary to consider the rest of the Pluto system. The largest moon circling around Pluto is called Charon. It is approximately 1 arcsec away from Pluto and is about 1/10$^{th}$ the mass of Pluto. In other words, the center of mass of the two objects is about 0.1 arcsec away from the center of Pluto. This is about the same distance by which Pluto missed the star. Did the center of mass of Pluto and Charon go over the star? It would make sense that the prediction of the occultation would be made for the center of mass of Pluto and Charon, rather than Pluto alone, because it is the Pluto system that is tracked.

For the center of mass of Pluto and Charon to go over the star, then they would have to be oriented perpendicular to the path taken for them to have missed occulting the star. To determine how Pluto and Charon were oriented during this observation, two different determinations were made.

The first determination, shown in Fig. 6a, is a long-term average of 1,000 frames near the beginning of the pass. The images were re-centered to remove the random tip-tilt shifts. In the image of Pluto in the lower left corner, the long-term average shows a bump in the upper left corner, implying that there is something there, perhaps Charon. It was just such a bump by which Charon was originally discovered.

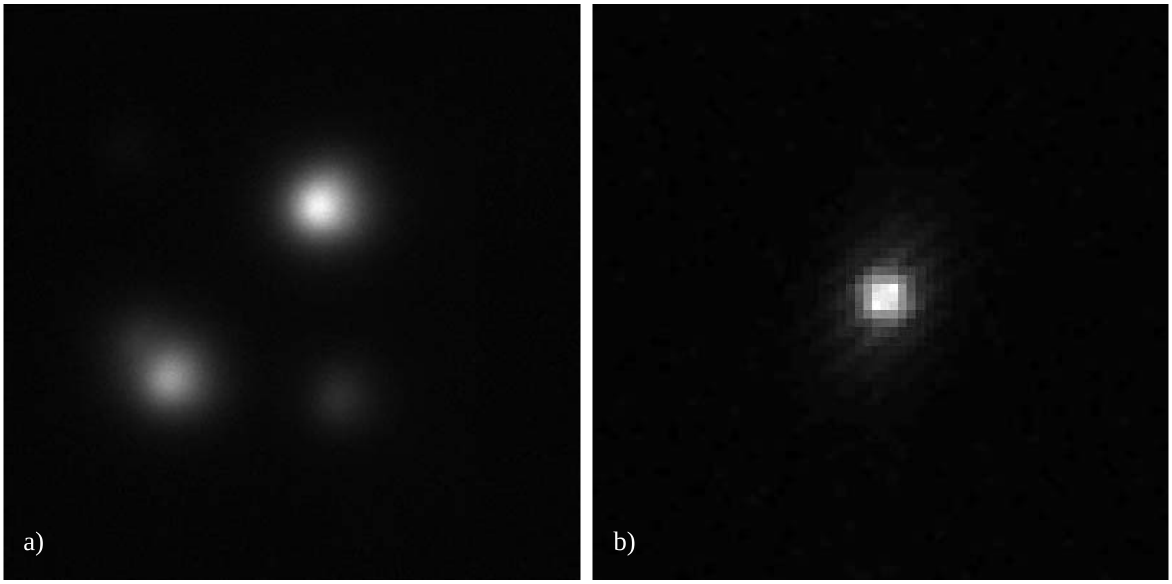


Fig. 6. a) long-term average showing a bump on Pluto, b) fringes from 1,000 frames showing the same orientation.

The second determination was made by applying Labeyrie's technique to the images of Pluto by itself. An average of 1,000 Fourier Transforms in Fig. 6b shows fringes oriented as if Charon and Pluto were oriented upper left to lower right. The fringes, of course, do not show which body is on the left and which is on the right, but the long-term average indicates that Charon is on the upper left. If Charon is located to the upper left of Pluto, then the center of mass of the system is between them. This is also where the occultation star is located, at almost the same distance from Pluto. This analysis therefore confirms that the center of mass of the Pluto system passed over the occultation star, but Pluto and Charon were oriented perpendicular to the path of the Pluto system. As a result, neither Pluto nor Charon passed over the star and no starlight was blocked by either Pluto or Charon, resulting in no data on the atmosphere of either body.

## 6. CONCLUSIONS

The analysis of an hour's observation on 29 June 2012 of Pluto and the star that it was supposed to occult, shows that Pluto missed the star by 0.135 arcsec. The center of mass of the Pluto-Charon system, which is 0.1 arcsec away from Pluto, passed almost directly over the occultation star. Unfortunately, Pluto and Charon were oriented perpendicularly to the direction of travel. As a result, the center of mass passed over the star, but both Pluto and Charon missed it. This gave a negative result for the occultation, yielding no information about their atmospheres from this near occultation.

## 7. REFERENCES

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