High Resolution Asteroid Profile by Multi Chord Occultation Observations

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Abstract

For millennia man has observed celestial objects occulting other bodies and distant stars. We have used these celestial synchronicities to measure the properties of objects. On January 1, 1801 Italian astronomer Giuseppe Piazzi discovered the first asteroid that would soon be named Ceres. To date 190,000 of these objects have been catalogued, but only a fraction of these have accurate measurements of their true size and shape. The International Occultation Timing Association (IOTA) currently facilitates the prediction and reduction of asteroidal occultations. By measuring the shadow cast on the earth by an asteroid during a stellar occultation one can directly measure the physical size, shape, and position in space of this body to accuracies orders of magnitudes better than the best ground based adaptive optics telescope and can provide verification to 3D inverted reflective lightcurve prediction models. Recent novel methods developed by IOTA involving an individual making multiple observations through unattended remote observing stations have made way for numerous chords of occultation measurement through a single body yielding high resolution profiles of asteroid bodies. Methodology of how observing stations are deployed will be demonstrated, results of some of these observations are presented as comparisons to their inverted lightcurve are shown.

1. Introduction

On January 1, 1801 Italian astronomer Giuseppe Piazzi discovered asteroid (1) Ceres. The database of minor planets would grow significantly before accurate predictions of stellar occultations by these rocks would be achieved. The advent of successful asteroidal occultation observation through predictions was realized in 1961 when (2) Pallas was photoelectrically recorded briefly blocking the light of a star at Naini Tal Observatory in India (Sinvhal et al, 1962). It would not be until the mid to late 1970s until an accurate star catalogue by Hipparcos would help generate repeatedly accurate predictions of minor planet occultations (Dunham, et al, 2002). Asteroidal occultations are a key tool for measuring the size, shape, and position of these minor planets.

Satelloids to these minor planets were first discovered through occultation data as well. On March 5, 1977 Paul Maley detected a secondary occultation event apart from the primary occultation of gamma Ceti by (6) Hebe. As of December 2006 some 42 possible satelloids have been detected through asteroidal occultations (Maley, et al., 2007).

Key for the value of the occultation observation is that there be as many positive (occultation detected) and negative (miss) observations spaced across the path(s) of the parent and/or secondary object. Well spaced positive detections establish both shape and astrometric measurements, while misses are also very important to place bounds for parent bodies and separation for secondary bodies.

2. Methods

2.1 Event Timing

Occultation timing measurements can be carried out through a variety of equipment configuration methods. For an in depth discussions on this refer to "*Chasing the Shadow*" (Nugent, 2007). For the purpose of this paper I will briefly describe here that visual timings of the disappearance and reappearance of a target star can be made with a tape recording of a timing source broadcast while audibly calling out the events. Photoelectric detection and CCD camera drift timings are another means of increasing the accuracy of detection. More recently with the proliferation of highly sensitive black and white CCD security cameras one can video tape through a telescope the star's intensity and remove all observer bias from the visual method. Various devices are on the market that allows one to embed in the video image GPS UT time stamps accurate to sub milliseconds.

2.2 Observer Location Placement

The method used to document an occultation is secondary to the importance of their being multiple observations that are well placed along the path of the asteroid's shadow along the ground. Occultation data reduction from a single observed positive chord gives very ambiguous results. There is no way to put constraints on size, shape, or center of body measurements. Two well placed positive chords can yield better results in constraints on size, shape, and estimation of body center for astrometric updates. It is most desirable, however, to have a minimum of three well spaced positive chords, and preferable to have a miss chord on either end of these positives.

2.3 Historical Occultation Station

Prior to 2001 the typical occultation observing setup consisted of anywhere from your common backyard variety telescope aperture that was capable of being portable to a major observatory class observing system fixed in location. For a fixed location observer, one had to wait for an event to occur near them. For a portable observer one could take their equipment mobile on an expedition to the predicted shadow path and increase the statistical likelihood for a positive measurement. All observations to that point in time were done, however, with one person manning one observing station. This routine was certainly statistically better than no observations being made, but this certainly had its limits as to the number of chords one could ever expect to achieve per asteroidal occultation.

On September 7, 2001 David Dunham would be the first person to record 2 positive occultation timings from a single event, an occultation by (9) Metis (Dunham, 2007). He would set up one portable station and leave it unattended to run autonomously while deploying a second station in another part of the predicted shadow path. David Dunham, Roger Venable, Steve Preston, and Dave Gault, to name a few, would forge a new endeavor for IOTA, multiple chord observations by a single person.

2.4 Miniaturization of Available Equipment

Miniaturization of retail electronic equipment has provided the average consumer a number of options for portable electronics. One pound miniDV camcorders can provide a digital near lossless recording of a video signal. Handheld GPS devices can replace large bulky maps for locating your site on

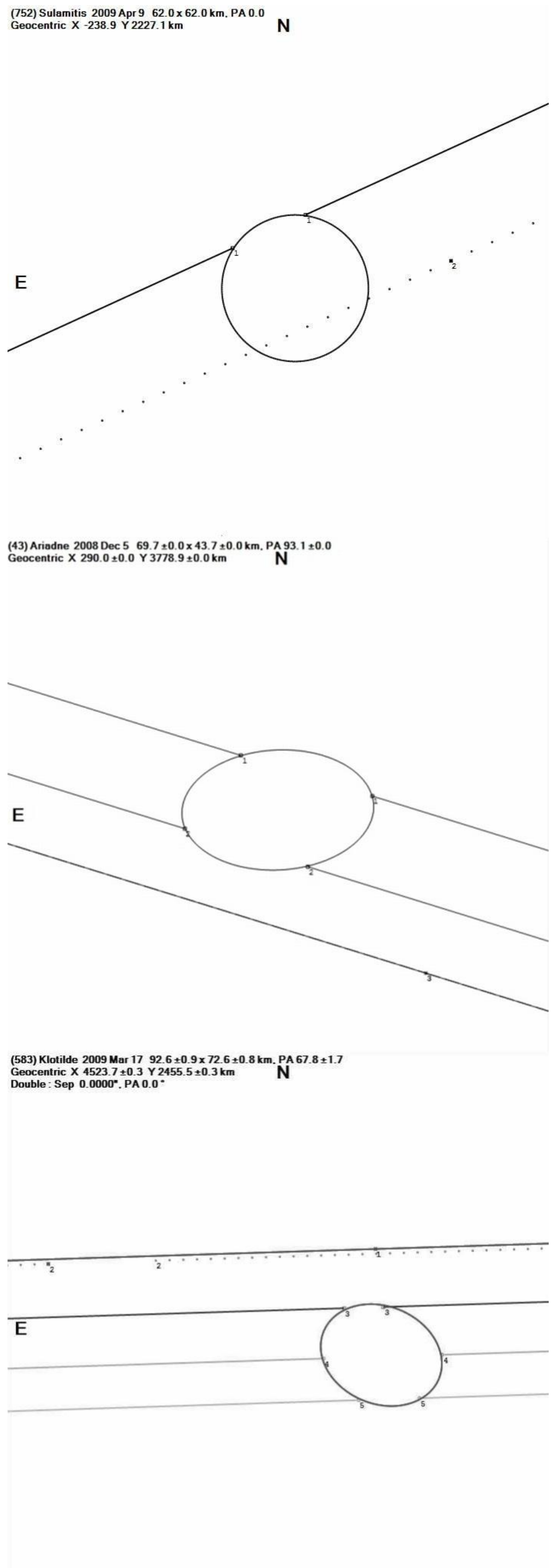

Figure 1

the ground and documenting one's position with unprecedented accuracy. CCD cameras smaller than eyepieces can record with high sensitivity a star's light, and given the NTSC video rate of 59.94 fields per second, can provide a data stream with 0.017 seconds of time resolution, which equates to tens to hundreds of meters of spatial resolution of the asteroid (one to two orders of magnitude higher than ground based adaptive optics). New battery technologies such as Lithium Ion and Nickel Metal Hydride (NiMH) can provide power sources compact, yet with high capacities.

2.5 Novel Multi Chord Approach

A recent invention of mine where I take the 50mm objective lens from a common pair of binocular and mount it straight onto an Owl focal reducer adapted to a highly sensitive security video camera now provides an observing system only 8 inches long, yet able to detect stars to 10^{th} magnitude in a 3.2 X 2.4 degree field of view (Degenhardt, 2009). This new optical system was dubbed by David Dunham as the "Mighty Mini." Further experiments with an Orion 80mm Short Tube Refractor (ST) would show that another order of magnitude in sensitivity with half of the Mighty Mini field of view could be attained in an also very small package compared to your average backyard telescope. Combining the Mighty Mini, 80mm ST, and all of the miniaturized electronic ingredients into one package one can have a complete portable occultation observation station that weighs only about 10 pounds. There are more than a dozen occultations per year in reach by this setup. Such compact observing stations also means that one person can go on a mobile occultation expedition with a dozen or more portable stations, even traveling by air, with much less effort than in the past.

Figure 2

2.6 Deployment Techniques

Streamlining the deployment of a high number of unattended observing stations became essential to minimize wasted efforts due to data failures. Over the course of 2008 David Dunham and I would propose and test numerous equipment and deployment techniques. Others in the IOTA group would also attempt multi chord deployments and lend advice through our Yahoo Discussion Group. Even Bill Gray would offer one of the most significant tools to assure that each station could be prepointed to the proper part of the sky. Gray modified his Guide 8 star chart software so that one could automatically generate a time trail backwards in time on the sky chart showing where the correct altitude and azimuth of the target star would be at event time so that arriving at any site at any time prior to the occultation you could accurately and quickly determine where to aim (Gray, 2009). KIWI Geoff, maker of the KIWI OSD UT video time stamp, devised a fool proof method of quickly laying UT time on the video and being able to disconnect the OSD unit without disrupting the video sync signal, thus preserving the frame count for post event time reduction (Hitchcox, 2009).

What emerged was finally a repeatable technique that I personally employed. I dubbed my two techniques the "Stamp & Run" and the "Deploy and Run."

In a Stamp & Run one would prepoint as many stations as possible to the correct altitude and azimuth of the target star at event time prior to the event time minus the record length of your tape. So if your event was at 05:22UT and your tape length is 120 minutes, then until 03:22UT one would prepoint as many stations as possible. Then at 03:22UT one would begin the recording at the last station prepointed, lay a UT time stamp at the beginning of the tape, and travel as fast as you could to each station doing the same until you reached the first station prepointed.

The Deploy & Run is different in that this technique occurs within the record window of your tape length. So using the time example previously, at 03:22UT I would prepoint the first station, start recording, and time stamp it, i.e. a complete deployment all at once, and then travel as fast as I could to the next station. I would Deploy & Run as many stations as I could up until the occultation has occurred.

The advantage of the Stamp & Run is one can usually end up with more observing stations because you have more time. In cases where an event is right up against evening twilight one does not have the luxury of that extra time and has to use the Deploy &

Run instead. Post event statistical analysis of my GPS data shows that my average time for prepointing a station is between 6 and 8 minutes and the time stamp process required an additional 3 to 4 minutes. A Deploy & Run station would take between 10 to 12 minutes (all times not counting travel time between stations).

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2.7 Deployment Field Tests

September 12, 2008 (9) Metis would be the first dedployment field test of an array of Mighty Minis. The 2008 annual conference of IOTA was scheduled around this event in an effort to have a large number of chords for this statistically high ranking event. I planned on deploying a total of 15 Mighty Minis at the northern edge of the predicted shadow path, each spaced a few kilometers apart, in an effort to get a high resolution map of this edge of the rock. David Dunham deployed an array of Minis and other instruments at centerline.

September 26, 2008 (216) Kleopatra, only two weeks after the (9) Metis event David Dunham and I would push the remote multi station occultation deployment envelope to its limits. We would both travel to the remote region of Fort Nelson, B.C. in an effort to verify whether Kleopatra is indeed dog bone shaped or binary. I would travel by three different airlines with 21 complete occultation stations and David would bring just under a dozen. I would deploy north of centerline with 3km to 5km spacing to the north 1 sigma prediction line. I succeeded in prepointing 16 stations, but was only able to reach 14 to start recording and apply the time stamp. David would deploy south of centerline as many stations as he could. He succeeded in getting 5 stations going, but one recorder failed to collect data.

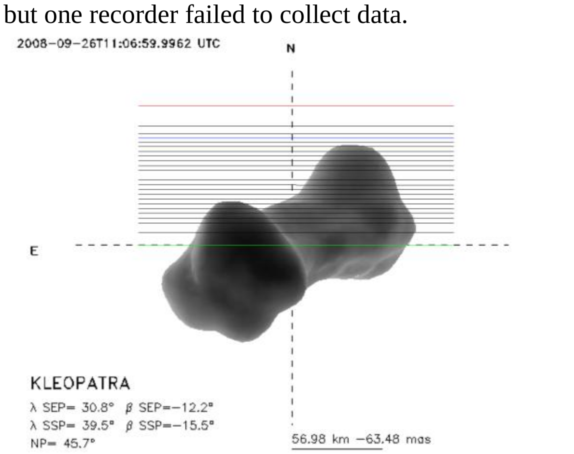

Figure 3

December 11, 2008 (135) Herth event would be one for the record books. I would succeed in deploying 10 Mighty Mini and 5 80mm ST complete stations, all of which were in Hertha's shadow. One 80mm ST station was stolen, but the remaining 14 stations were all successful in reporting 14 positive events by a single person.

3. Results

September 12, 2008 (9) Metis. Josef Durech (Durech, 2009) provided a predicted orientation for Metis based on inverting its reflected lightcurve (Durech, 2009) and had predicted that the northern edge deviated from a round fit and was rather long and flat. The inverted lightcurve 3D model turned out to be spot on correct and all 9 of the stations I deployed that successfully recorded the target star showed no occultation detected (all misses). 31 positive chords were recorded however, most significantly three of these chords were from David Dunham's Mighty Mini stations, making his the very first positive events recorded with this new observing instrument.

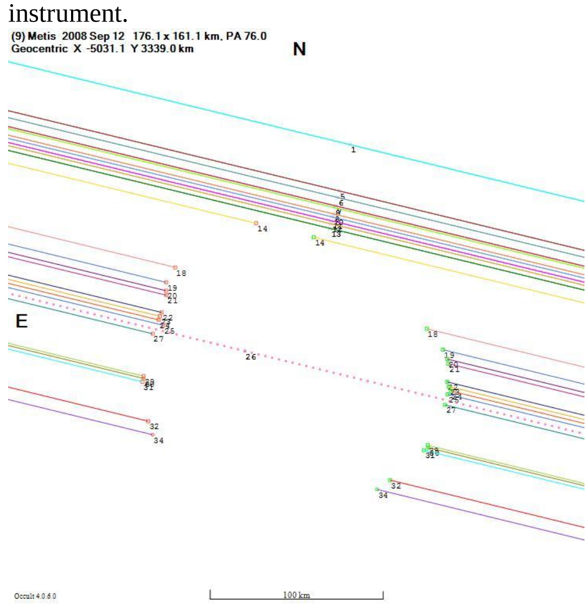

Figure 4

September 26, 2008 (216) Kleopatra. The actual path of Kleopatra shifted 13 sigma south from the predicted path. All 14 of my Mighty Mini stations recorded misses as well as 2 of David's stations. Out of the nearly 20 stations deployed between David and I, only two positive chords where recorded by David's southern most stations, thus revealing this path shift. Despite the effort seeming to be unsuccessful, the field test of our deployment methods would go a long way to assuring future successes such as (135) Hertha event in December 2008.

December 11, 2008 (135) Hertha.

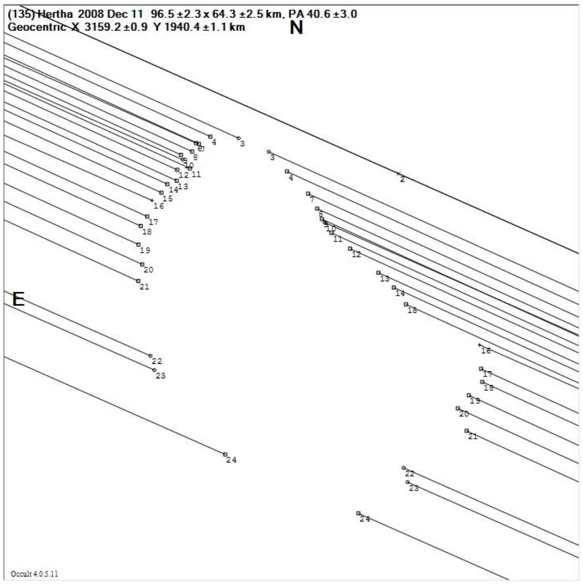

Figure 5

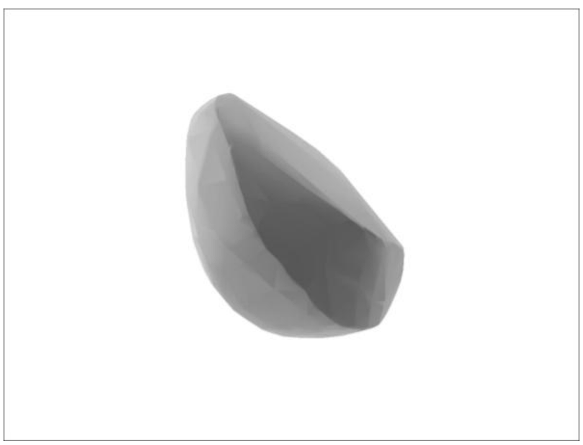

Figure 6

The graphical results sort of speak for themselves. I would provide an unprecedented 14 of the 22 positive chords toward the Hertha occultation profile, finally demonstrating the significance that one multi chord effort can make. With this high resolution profile of Hertha we were able to compare through post analysis the inverted lightcurve model from Durech and determine the excellent fit between the two reductions. A reflective lightcurve was derived by Brian Warner at his Palmer Observatory (Warner, 2009). This light curve also verified that Hertha was at near peak intensity, thus maximum elongation in orientation at occultation event time.

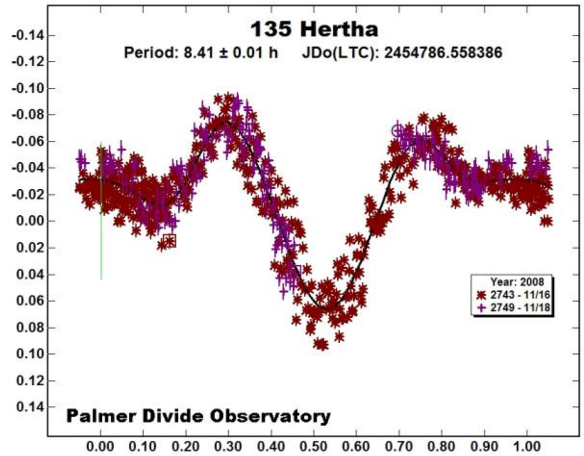

Figure 7

4. Conclusion

Numerous other multi station deployments were achieved both before and after these three featured events. Emerging trends have become clear. The number of events that have more than one station per observer is increasing, thus the quality of occultation data is improving. Also, the quantity of extra stations per person is sharply on the increase due to both the equipment miniaturization effort and the psychological effect of others wanting to be one that contributes multiple chords for asteroidal reduction profiles.

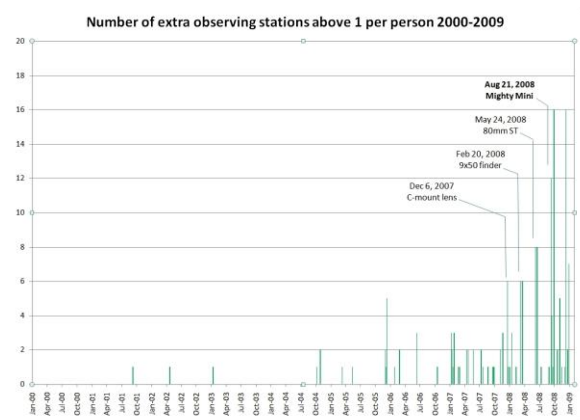

Figure 8

High resolution occultation measurements can also detect and measure single and multiple body systems with great detail. Given that occultation lightcurve data can provide one to two orders of magnitude greater resolution information about an asteroid’s profile than even the best ground based adaptive optics observation, it is essential that both the effort on the part of observers and funding for these observers increase to facilitate high resolution asteroidal profile data.

The synergy between the reflective lightcurve, inverted lightcurve, and occultation lightcurve disciplines is obvious. I believe a consortium of some sort needs to be formed between these three to form a united minor planet documentation effort. The value of each data to the other has become apparent after recent occultation events.

Future events will also require a group effort. On November 21, 2009 (234) Barbara will occult a relatively bright star. Barbara was recently listed as a possible binary object after the team of VLTI-MIDI determined this through a new interferometric imaging technique (M. Delbo, et al., 2009). A high resolution occultation profile of Barbara would go a long way to validate this new imaging technique by the VLTI-MIDI team.

As of the writing of this paper an even newer deployment technique is on the horizon. Programmable remote controls commonly found on the retail market can now allow a scheduled record for unattended remote stations. This will widen the deployment distance and number of stations window such that a 20 station deployment over more than 100km may become easy to deploy (given ample dark time).

5. Acknowledgements

Figure 1 asteroid profiles were reduced by Brad Timerson using *Occult 4* (Herald, 2009). Observer(s) for April 9, 2009 (752) Sulamitis is George, T., December 5, 2008 (43) Ariadne is Degenhardt, S. (2 positives), March 17, 2009 (583) Klotilde are Jones, R., Lambert, R., Lucas, R., Maley, P., McGaha, J., and Nye, D., September 12, 2008 (9) Metis are Benner, L., Blanchette, D., Breit, D., Carlisle, R., Clark, J., Coughlin, K., Degenhardt, S. (9 misses), Dunham, D. (3 positives), Hicks, M., Jones, R., Lucas, G., Lyzenga, G., Morgan, W. (2 positives), Nolthenius, R., Nugent, R., Royer, R., Sanford, J., Sorensen, B., and Vincent, M. (2 positives).

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7. Figure Captions

Figure 1 demonstrates that a single chord positive event (top) is ambiguous. Only a circle fit can be used, and a guess has to be made as to whether the body is on one side or the other of the chord. A well spaced profile with 2 positive chords (middle) gives better results for both approximate size and center of body. 3 or more chords (bottom) give good constraints to size, shape, and astrometric position.

Figure 2. The complete Mighty Mini portable station.

Figure 3. The Durech (courtesy Durech, J., 2009) inverted lightcurve model showing the predicted orientation of (216) Kleopatra on September 26, 2008 at event time with my proposed 20 station deployment chords drawn across showing the intended measurements to be made by the actual occultation.

Figure 4. The profile of the September 12, 2008 (9) Metis occultation (courtesy Timerson, B., 2009) showing how 31 positive chords can give great detail of the Metis shape. Also of significance are the 3 positive chords by David Dunham which are the first positive chords for the Mighty Mini.

Figure 5. The December 11, 2008 occultation profile of (135) Hertha (courtesy Timerson, B., 2009). Of significance is that 14 positive chords were recorded by a single observer, Degenhardt, S. (Degenhardt, S., 2009). The other observers were Dunham, D., Holmes, A., Lyzenga, G., Maley, P., Mroz, G., Owen, B., Stanton, R., Wasson, R., Young, J..

Figure 6. The Durech 3D lightcurve inverted model for the predicted event time for the December 11, 2008 (135) Hertha occultation (courtesy Durech, J., 2009)

Figure 7. The (135) Hertha reflected lightcurve kindly provided by Warner B. acquired at Palmer Observatory which allowed us to confirm that Hertha was at a phase of 0.72 or near full elongation during the December 11, 2008 occultation. (courtesy Warner, B., 2008)

Figure 8. My statistical analysis I derived of the number of extra observing stations above 1 per person from January 2000 to January 2009. An increase is noticed beginning in late 2007 when common C-mount camera lenses were found to be useful for the brighter occultation events, followed by a sharp rise upon the introduction of the Mighty Mini and then the Orion 80mm ST. (courtesy Degenhardt, S., "Effects of Optical Miniaturization on Occultations," 2009)