

High Precision Astrometry of Occultation Asteroids

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Abstract

Astrometry is a subfield within astronomy, which is interested in recording the positions of celestial objects by using celestial coordinates. Typically this is done by using measures of the object's right ascension and declination. Our application of astrometry is interested in the positions of minor planets, particularly asteroids, before they occult. We are able to do this by using a 0.6 meter telescope, which is attached to a sophisticated camera, a charge-coupled device, at the Table Mountain Observatory. Before we are to take any pictures, we use a program referred to as ghostview to access postscript files of asteroid predictions, which are first determined by scripts that access and compute JPL's ephemerides. Thus, we can then print and modify the asteroid's right ascension and declination slightly by hand, and proceed to use our new coordinates as an indication of where to point the telescope. Once pictures are obtained for a night, we run various scripts to ensure the integrity of the data, and finally reduce said data before it sent to organizations such as the Minor Planet Center.

1. Introduction

The information we obtain by astrometry of occultation asteroids is substantial. By tracking the locations of asteroids, the orbital information concerning these celestial bodies can be further refined, allowing us to statistically infer more confidently when they are to occult. Furthermore, since orbital information could never be exact, accuracy of orbits would diminish over time without routine observation.

In addition, once space craft begins to transmit data by way of laser, we can use the same methods as used in determining the locations of asteroids, to

track the location of space craft. Indeed, astrometry has already proven beneficial in regards to space navigation.

2. Methods

Our work consists of three phases: Planning, observation, and data reduction.

2.1 Planning

The first step in planning is preparing plots, which is done within a UNIX environment. First, we run an update script within the terminal, which updates the target's position for whatever date(s) we are interested in observing. In general, the update command is of the form,

update [year] [month] [day]

Say we were to observe the night of July 16th. While bearing in mind that we go by Universal Time, i.e., a day later, we would input the command like so,

update 2014 JUL 17

Depending upon the observation schedule, we may have the telescope for up to three nights. In which case, we can cover all dates by inputting,

update 2014 JUL 17 2014 JUL 19

Once we've run the update, we access JPL's ephemerides by running a script which follows the general form of *pred*, but is notated by whatever camera we happen to be using. For example, if we were to use the 4K FLI camera, then we would input,

pred4f

However, as we used the 2K CCD camera most of the time due to technical failures on part of the 4K, we would input,

pred2k

These scripts are unique, that is, they are separate programs. However, they serve the same functions – and are unique only in the sense that they are written specifically for their respective camera.

What we are left with from inputting these commands are a set of postscript files, which are accessible by using the *ghostview* program. Simply put into the terminal as,

gv

We do adhere to criteria when selecting targets to observe, as not every target will be suitable for observation. In general, we will avoid any target with a beta angle that is less than 90 degrees, or has an angle of declination south of -30 degrees. Furthermore, a good target, or plot, will have plenty of reference stars. It is also important to check schedules. A schedule file is of the form, for example, *schocc1406a.psf*, representing the scheduled occultation of minor planets for the year (2014) and month (06). By overlooking the schedule files, we could wind up observing asteroids long past their date of occultation, which would be futile.

In the last phase of planning, we print the plots chosen from *ghostview*, and begin to modify the targets right ascension and declination. We do this by hand, with a transparent overlay, unique to whatever camera we are using to correct for offsets. We “slide” the overlay around the center of the plot, performing arithmetic of the right ascension and declination, giving us the coordinates used in the observation phase. For each target, we make anywhere from two to five modifications, which turns out to be two to five pictures of each target.

2.2 Observation

Observation is done at the Table Mountain Observatory, overlooking Wrightwood, California, at an elevation of 7,500 feet. Our work was done in

building TM-12, with a 0.6 meter telescope. For most of our observations we used the 2K CCD camera.

Before we begin observing for a night, there are a couple steps we must take. The first is raising the platform within the observatory to turn off the air unit. The air unit is usually set between 50 to 60 degrees, but is dependent on the projected temperature of the following evening. At sun set, we begin executing the programs which are used to control both the telescope and camera.

The programs we use are executed in a specific order: *TCP*, *Dome*, *Positions*, *Focus*, and *Paddle*. All of these programs are used to control the telescope, and *TCP*, telescope control program, is dependent on them to function properly. For the 2K camera, we execute *2K SI IFW*, *2K SI Trigger*, and *2K SI Image*.

Once the programs are initialized, we create the directory, which corresponds to the date we are observing (e.g. 14224, indicating year and day), along with two text files – *point[date]* and *temp[date]*. Both text files essentially reflect a physical observation log, but are used in the data reduction phase.

The *point* file contains information of each picture taken. It contains each target's right ascension, declination, and prefix. The prefixes are identifiers of each target. The asteroid Piazzia has the prefix *pzz*, for example. During one night of our observations, we logged Piazzia like so,

21 30 10 ; -17 03 ; pzz

The *temp* file contains information on the weather at the time of each target's sequence of pictures. Humidity, barometric pressure, temperature, and of course, we include the object's prefix. We input the information into the *temp* file like so,

pzz 57 22.83 43

The form is of prefix, temperature, barometric pressure, and humidity.

After the dome is opened from its respective client, we select the position *J2000* in the *Positions* client, which ensures the telescope tracks correctly. We then begin calibrating the telescope and camera.

Calibration is done by selecting a star near the zenith in the *Positions* client, by using the *Astrometric* catalogue. One of our tools, Pulnix, is a camera that transmits a live feed of where the telescope is pointed to a small RCA television, which is positioned by the monitor in which we control the telescope and camera. By simply looking at the RCA screen, we can use the *Paddle* client to manually move the telescope until the star is centered on screen.

With that done, we begin focusing the camera in the *Focus* client. While testing the focus, we normally have exposure set to 3-seconds. In our experience, using the 2K camera, we found a focus of around 205 to be most ideal.

The next step is to set the exposure to 120-seconds, the filter to R, and begin taking pictures. In the *Positions* client, we enter the coordinates we obtained from the planning phase, and then load them into *TCP*. Once we activate *TCP*, the telescope moves to the desired position, and we begin taking pictures. For each target, we wind up with a mosaic of images.

Historically, astrometry worked by what is referred to as the “six-constant” method. Thus, we’d have obtained our mosaic by reducing each picture separately. That is, we would take the measured (x, y) coordinate of reference stars, which would be combined with the known (RA, Dec) of reference stars, giving us a mapping from the (x, y) coordinate to the (RA, Dec) coordinate. By taking the measured (x, y) coordinate of an asteroid then, we could obtain the (RA, Dec) of the asteroid. By using three reference stars, we could get an exact solution. However, this method is largely dated, and is dependent on catalogued stars, as to where with our method, we can use stars that have not been catalogued – we could even use catalogues which are not most reliable and obtain suitable results regardless.

Our method is inspired by astronomer Heinrich Eichhorn, who introduced the “Plate Overlap” method in cataloging stars. In this method, the coordinates of an un-catalogued star, (x, y) , can be used by requiring the (RA, Dec) coordinate to be used across the set of images. What we are left with is more

precise mapping. In sum, the “six-constant” method is dependent upon catalogued stars, while with the “Plate Overlap” method, we can solve for more parameters, and gain more precise results, by using reference stars and un-catalogued stars.

It is worth noting that we do not take pictures in rapid succession. In some cases, we must exercise restraint. If we were to have a target whose right ascension is around 19, and yet the LST, local side-reel time, within the *TCP* client reflected a right ascension value of, say, 17, we could obtain better results by waiting for the LST to reflect more appropriate timing which corresponds to our target’s right ascension.

At some point in the night, it is necessary to take about five pictures of the “calibration field.” In our last two weeks of observation, our calibration field was the Wild Duck cluster, or as it’s more formally known, Messier 11. As the field is extremely dense, we obtain a precise solution. Thus, in the data reduction phase, when a target is reduced, our images of Messier 11 are brought in simultaneously.

After we’ve obtained every target’s picture, or at the beginning of daybreak, we shut the dome, and in the *TCP* client, stow the telescope. The final step of observation is transferring our aforementioned directory (14224), containing the *point* and *temp* files, along with our obtained pictures, from Murzim to Dubhe – which we can access

over the network from the JPL campus, and proceed to the data reduction phase.

2.3 Data reduction

Our final phase is data reduction. It starts by executing a script referred to as “*doit*,” along with the respective date observed. The *doit* script will execute four other scripts, “*prepare*,” “*amptemp*,” “*centroid*,” and “*reduce*.”

prepare serves the function of renaming the pictures we’ve obtained, along with reformatting them so that they may later be processed. *amptemp* utilizes the temp file, by creating input files. *centroid* establishes the center of every star-like image within the reformatted picture files, by seeking the local maximum.

The last script *doit* executes is “*reduce*,” and it runs four major programs itself. First, it runs the trajectory geometry program, or “*tgp*,” which provides predicted coordinates of stars, or the asteroid itself, which are thought to be either in or near the field of view. Secondly, it runs “*amp*,” which compares a list of observed images, as obtained from the *centroid* script, to the list of predicted images from the *tgp* script. Unidentified images are taken to be un-catalogued stars, sorted into a group which *amp* looks for again in other pictures. Byproducts of executing *amp* are a schedule file (as mentioned in section 2.1), a list containing all the observations with images identified, and finally a list which contains positions for

each target, catalogued star, and un-catalogued star found.

The last two scripts *reduce* calls are “*aopg*,” and “*adap*.” *aopg* calculates the expected (x, y) coordinate of the images as obtained from the *amp* script. The coordinates are subtracted from the observed (x, y) coordinates, which form the residuals. Then it computes the partial derivatives of the coordinates, with respect to the variables which were used to determine (x, y) . *adap* processes the data, and produces summary files, performing much of the mathematical calculations involved in our application of astrometry.

Data reduction can, and most often does, contain errors. By using scripts such as, “*findbad*,” we can mitigate most. *findbad* outputs a list containing images with a postfit residual greater than a pixel. Subsequently, we remove these images. We also use the script “*check*.” Inputting *check* allows us to see whether or not the number of pictures and targets we have are equal to the number of targets found. In some cases, particularly if a target was not found, as printed by the *amp* script, we can manually find the target by using the program *xrover*, and moving the overlay to its accurate position over the image.

3. Results

After our scripts have successfully reduced the data obtained from observation, there is one last script to run, “*deliver*.” This script condenses the

summary files as produced by the *adapt* script.

One of the recipients of the data we obtain is the Minor Planet Center. The Minor Planet Center processes the residuals from a consolidation of the summary files, to ensure the residuals match up with the targets. Assuming that there is a match, the data is then processed and added to their databases. If one were to look up the asteroid *Piazzia* through the Minor Planet Center, they would be able to access the bodies' data, such as orbital period, eccentricity, and so on.

A direct recipient of our data is the IOTA, the International Occultation Timing Association. The IOTA is an educational organization, consisting of occultation enthusiasts, as well as educators who seek to bring awareness to the general public of occulting celestial bodies. The IOTA uses our data to follow, and list, occultation dates of asteroids for observing purposes.

As our data is extremely useful in optical navigation, it is also used by scientists involved in the New Horizons project – a spacecraft on a voyage towards Pluto. We routinely observed Pluto specifically for this purpose, to contribute data that is used to improve the ephemeris of Pluto.

In total, we had three nights with the Finger Lakes 4K camera, and five nights with the Spectral Instruments 2K camera. We conducted 1,153 observations, observed 213 different

objects, and made 17 observations of Pluto. Four observations were made each of Jupiter's outer satellites: Himalia, Elara, and Pasiphae. One observation each was made of Saturn's satellites: Rhea, Titan and Iapetus, along with three observations of Phoebe.

Acknowledgements

Dr. William M. Owen, mentor, Paul McCudden, CURE director, David Falk, CURE sponsor. Research was conducted at the Jet Propulsion Laboratory, and the Table Mountain Observatory. This work was supported by National Science Foundation grant #AST-1156756 to Los Angeles City College.

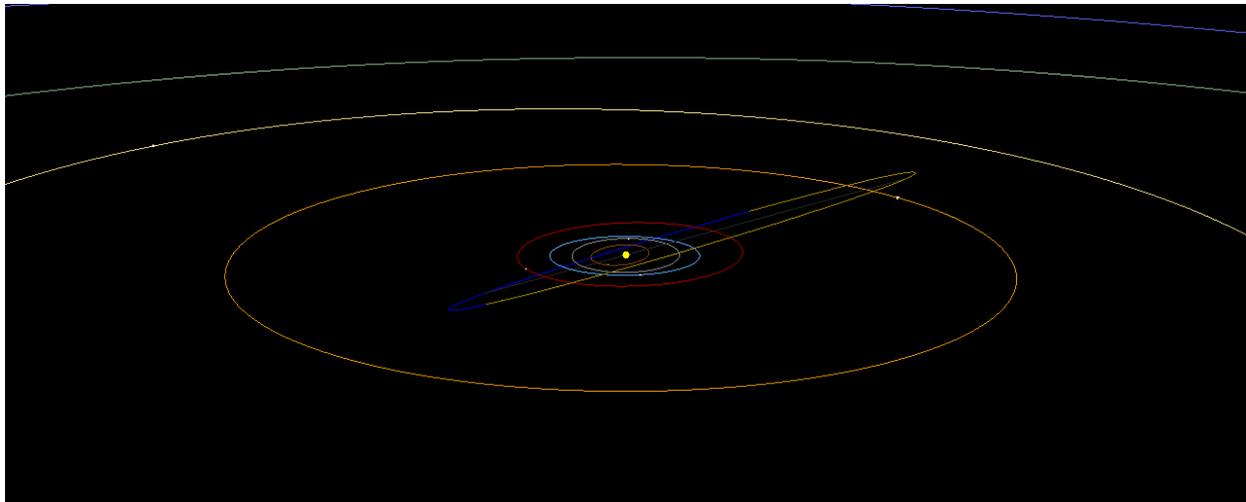


Figure 1: Piazzia orbital sketch from MPC database

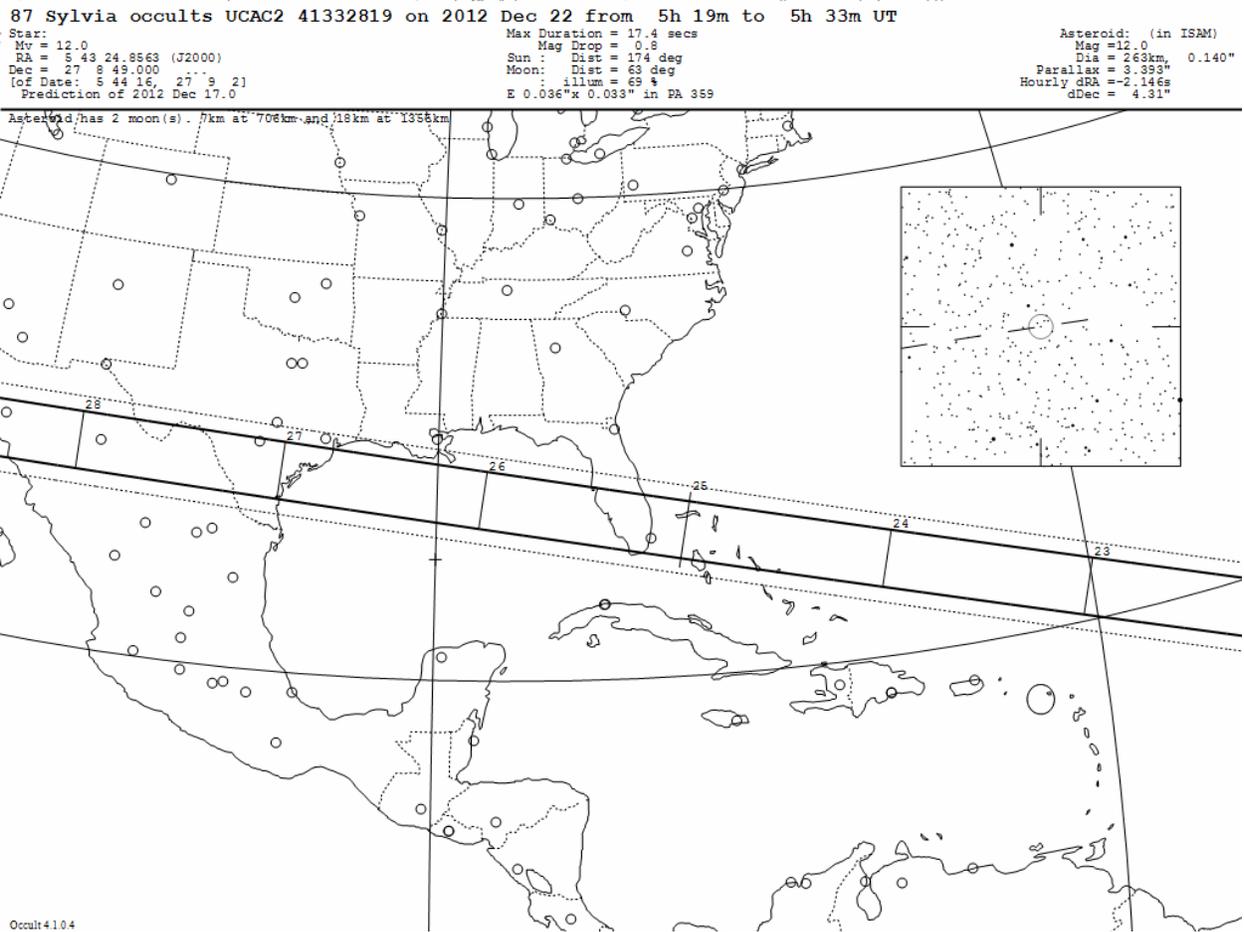


Figure 2: Sylvia's predicted path, from IOTA