High Precision Asteroid Astrometry

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ABSTRACT

This paper examines the use of astrometry for the study of occulting asteroids and the techniques used in this exploration. It details the preparation, observation, and data reduction methods employed throughout a project that aims to improve predictions for occulting asteroids by updating their positions in the sky. The imaging and study of asteroid occultations results in characterizing of the asteroid. This project lead to updated positions of asteroids and other satellites that can be helpful for other NASA projects and research.

I. INTRODUCTION

Astrometry is a subsection of astronomy that specializes in measuring stars' positions in the sky. The high precision astrometry of asteroids precisely measures the positions of asteroids. Astrometry is a good supplement to other types of observing such as spectroscopy and is helpful for providing long period observations. High precision asteroid astrometry provides an economic, efficient form of asteroid exploration and study.

II. PUPOSE

Our project's purpose was to image main belt and Trojan asteroids. By doing so we were able to update their ephemerides, data that gives the calculated positions of a celestial object at regular intervals throughout a period. We also assisted in forming more precise asteroid occultation predictions. An asteroid occultation is when an asteroid passes in front of a star. Successful observations of occultation events by many observatories around the world help to characterize the asteroids that occult. The results of a captured occultation event can describe the asteroid's shape and size. Predicting and recording asteroid occultation events prevents the need to send spacecraft to every asteroid in our solar system to study them. This work was performed with my partner, Allan Alonzo-Ault, and under the guidance of our mentor, Dr. William Owen.

III. EQUIPMENT

Observations were made using a 24 inch Astro Mechanics Ritchey-Chretien reflector telescope located in TM-12 at Table Mountain Observatory (TMO) in Wrightwood, CA and managed by NASA's Jet Propulsion Laboratory (JPL). We used two computers (Tucana and Dubhe). Tucana is located at JPL and used to perform predictions and remotely access Dubhe, while Dubhe is located at TMO in TM-27 and receives all of our observation files. To image the targets a ProLine PL16803 CCD camera was used, which is connected to the telescope. It takes 4096x4096 pixel images.

IV. PREPARATION

Before traveling to TMO, we chose the asteroids we would image during the three-night observation run. Asteroids were chosen based on magnitude, zenith, right ascension (RA) and degree of declination. Using a Trajectory Geometry Program (TGP) that is part of the Optical Navigation software at JPL, we were able to predict when and where a target asteroid would be each night. We open these prediction files in Ghostview (Fig. 1) to see the predictions generated by TGP.
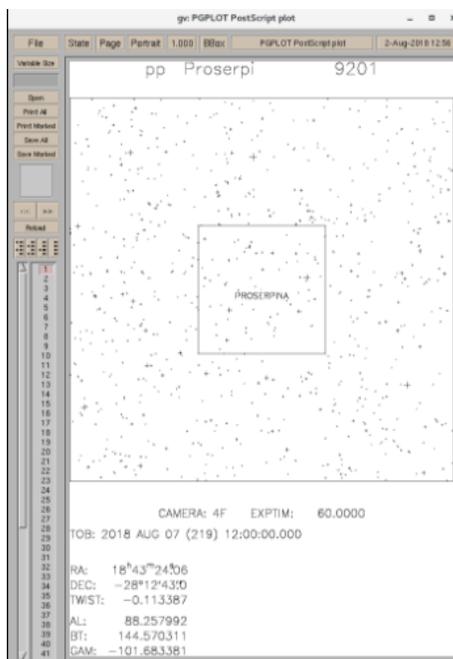

Fig. 1. Prediction file in ghostview of a viable target.

We chose asteroids that would be close to the zenith throughout the night because it allows us to look through less atmosphere when viewing the target. This results in less noise and distortion in the image, leading to more precise position calculations of the asteroid. To achieve the most accurate predictions of our targets' positions, we took advantage of three prediction updates per night to pinpoint target location near the local meridian. Our criteria for choosing targets involved an RA close to the zenith, a target with as many reference stars as possible, and a declination angle greater than -30°.

V. OBSERVATIONS

Observations took place using the telescope and camera at TMO. Most of this was done on-site, but some observations were performed remotely from JPL. A Windows computer at TMO was used to control the telescope and camera.

Our observing began with calculating RA and declination offsets for each target. These offsets allow us to take multiple images of the target, each with different pointing, meaning our images are never centered on the target. These calculations are done at the beginning of the night and then throughout the observing period as more targets are needed. Offsets are calculated using the prediction files produced by TGP (Fig. 1) that were printed while at JPL. We use overlays for these offset calculations, which are transparent pages we lay over the prediction files. They contain tick marks for us to measure shifts in RA and degrees of declination. For dense star fields around a target, we generally shift about ten seconds in RA on either side of the target and about two degrees of declination up and down. These shifts vary when the star field is sparse. We have five different overlays to use depending on the declination of the target.

Once we have logged into the Windows computer located in a room next to the telescope dome, we open the programs necessary for our observations. This gives us the power to open the dome shutter and remove the cover of the telescope. After we have done this, we use the focus client to focus the camera. To achieve focus we choose a dim star near the zenith of about 7 or 8 magnitude. By imaging this target with ten second exposures at 8MHz, we try to get the sharpest light profile of the star. We then use the paddle client to manually adjust the position of the telescope in small

increments to center the target star at 2048 by 2048 pixels. We calibrate the telescope at this position.

One of the most important programs we open is the Telescope Control Program (TCP). This program makes use of a tool called the position client. The position client allows us to input the right ascension and declination of the offsets for the target we want to image. These positions are then loaded into TCP which moves the telescope to the pointing we have assigned in the position client. TCP also reads the Universal Time, Local Sidereal Time, error, the secant z of the target, and tells us how far away in RA we are from the local meridian.

Once these programs are set and the camera is focused, imaging is possible. We use two windows for this, one that controls the camera and allows us to set the exposure time and readout speed, and another that allows us to view and save the image. Each image we take of a target is a 180 second exposure at 1MHz. We image each target two to three times, with different pointing, downloading and saving each image. Multiple images of the target are essential to our data reduction. Two images are satisfactory for a target with a rich field of stars around it, while three images is helpful when the surrounding star field is less dense.

Throughout the night we keep not only a written log, but also two text logs on the computer. The first is called the point file. In this file, we record the RA and declination offset calculations, as well as the prefix of the target, for each image that we take. The other text file we use is labeled as the temp file. We use this to track the current temperature, barometric pressure, and humidity for each target. Both the point and temp files are extremely important in our data reduction.

Imaging a calibration field while observing is essential for good data reduction. Throughout our project we used the the Wild Duck Cluster, also known as M11, for our calibration field. We chose this field because it is an extremely dense star field, containing about 2900 stars.

Throughout the night, the observing process is repeated for every target. Each image is taken and recorded the same way on the logs. Offsets are calculated throughout the night. Occasionally the camera will go out of focus, making a refocusing necessary.

By the end of the night we will have imaged about fifty targets two to three times each. We save the images and the point and temp files in a folder that can be accessed on the Dubhe computer for data reduction.

VI. DATA REDUCTION

After observations are finished, data reduction can be performed. This reduction turns pixels in a file into the RA and declination in the sky. The data reduction is done from JPL accessing the Dubhe computer at TMO. The data reduction scripts were written by Dr. Owen. Most were written for Optical Navigation at JPL and then adjusted to fit our needs. They are Unix based command scripts that are extremely powerful. Most of the reduction is autonomous. We only step in to call on the scripts or make adjustments. These adjustments are to correct our own error, locate faint targets, or delete bad residuals.

The scripts use multivariate linear least squares as the mathematical basis for the reduction calculations that they perform. They solve directly for changes in RA and declination of the telescope and the stars. They also solve for rotation angle, focal length and the aspect ratio of the pixels. After solving for these, they then add in the 2nd through 5th order terms using products of Legendre polynomials. These polynomials are used because they have the property that if the stars

are uniformly distributed, the solution for each one will not be statistically correlated with the others. This is the case because they are orthonormal. Results that contain stars that are not statistically correlated allow for more accurate and precise calculations of the data.

There are a few techniques that take place during observation that are done due to the needs of scripts used during reduction. The first is multiple rather than single images of each target taken with different pointing. For our data reduction technique to work, we need at least two different images of each target. By taking two or three images of each target with different pointing, we get information about the telescope distortions by seeing how star patterns change in each image. If we only have one successful image of a target, we cannot reduce its data and have to delete that target.

The calibration field is another aspect of data reduction that begins during observation. We take five different images of our calibration field while observing. This calibration field is applied to every image that is reduced. The calibration field tells us how the telescope and camera are behaving that night. This is extremely helpful for targets that do not contain enough reference stars for us to deduce camera and telescope behavior purely from their images.

The point and temp files also come into play when it is time perform data reduction. These files are read directly by the reduction scripts. They act as a guide, telling the scripts everything they need to know about the images that they cannot gather purely from the image itself. It is extremely important that these files do not contain any typos. A mistype of a prefix or pointing can cause major problems in the reduction. We go through these files to check for any typos before giving them to the scripts.

The first script called for reduction is the doit script. This calls four scripts of its own that are very powerful. The first is prepare. This script renames and reformats each file to convert the FITS images into the file format we use. Amptemp is next. It uses the temp file to create input files to be used throughout the reduction. Centroid follows amptemp. It goes through each picture file, top to bottom, looking for pixels that are brighter than those surrounding it. When it finds one that it thinks may be a star, it attempts to find the center of it. If it succeeds, it writes the results out to the .obs file.

The last script to run from doit is called reduce. Reduce calls on four other programs. The first is the TGP, which provides coordinates for predicted stars or the target asteroid. Next is AMP, which figures out which of the detections that the centroid script made are reference stars and which one is the target. The bright spots that cannot be matched as either the target or reference stars are logged as uncatalogued stars. The final two programs the reduce script uses are AOPG and ADAP (Astrometric Data Analysis Program). AOPG calculates expected (x,y) coordinates of images which are subtracted from observed (x,y) coordinates. This leads to the residuals. AOPG also calculates partial derivatives of the coordinates using the variables for determining (x,y). ADAP then processes these calculations and makes summary files.

Once reduce has finished, the check script is executed. It checks to see if the number of targets predicted to be in the images equals the number of targets located in the images. If a target is not found, we use a program called Xrover (Fig. 2) to manually locate the target. The program loads a Picture Sequence File (PSF) overlay. This locates the predicted location of the stars and target. We are able to manually shift the PSF to locate and line up the target. The new shifted PSF is then saved. After running
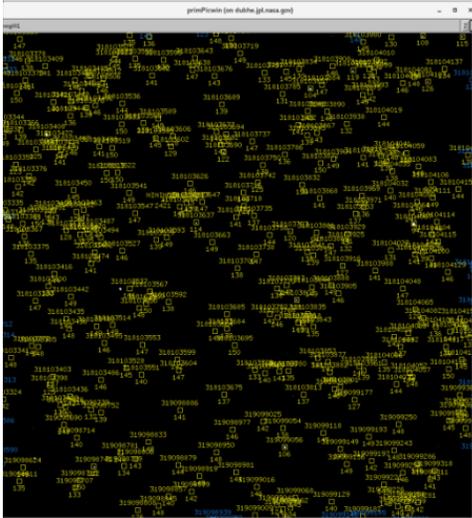
Fig. 2. Xrover program with PSF overlay.

Xrover on every image with a mismatched target, we use a script named ctrpsf on each image that was adjusted. This script results in a text file for each target that can then be opened in a text editor. We open this file and delete all the stars, both reference and uncatalogued, that are listed. We leave behind only the target. This gives the reduce script a better chance of locating the target. When we run the reduce script again after performing Xrover and running ctrpsf, we hope that all targets will be matched. However, sometimes the target is too faint to ever be found regardless of this manual manipulation of the PSF overlay.

Doit is the other script that is run to search for error after reduce is finished. It supplies a list of images that contain "bad residuals." A bad residual is anything bigger than one pixel. We delete the stars with bad residuals by commenting them out of their input files, which are read by ADAP. When we run the reduce script again, we hope that we will have successfully commented out any bad residuals from the images.

We continue this process of reduce, check, doit, reduce again, until the targets that can be matched have been matched and all bad residuals have been commented out. Once this is achieved, the bulk of data reduction is done. However, we still have two more scripts to run. The deliver script comes next. It condenses the summary files as produced by the ADAP script. A file is then created in our text editor that we can edit to credit observers and measurers. This file gets sent to the Minor Planet Center, to a few people in the occultation community and to a few people at JPL whose job is to update the orbits of the planets and their satellites. The final script we run is called cleanup. This script reconstitutes all of the picture files and compresses them so they can be stored without taking up too much space. This results in a TAR file that is zipped and stored.

VII. RESULTS

Throughout the course of our project we took 678 images while observing and imaged 145 unique objects. This lead to 519 positions of celestial objects obtained. By the end of the summer we had eight successful deliveries to the Minor Planet Center.

We also imaged Saturn's satellites during our project. This resulted in the update of the positions of six of the satellites. The satellites updated were Titan, Rhea, Tethys, Hyperion, Dione, and Iapetus. We also attempted to image Mars' satellites, Phobos and Deimos, when Mars was in opposition but were unsuccessful in doing so.

On July 13, we participated in an occultation event remotely from JPL. We had a 60% chance of viewing the occultation from our telescope at TMO. Unfortunately, we were unable to image the occultation event due to it being out of our path.

On August 22, we participated in another occultation event remotely from JPL. This time our chances of viewing it were higher. The event was taking place

only a few degrees from the moon, so we were unsure if the light from the moon would block the event for us. Luckily, we were able to successfully view and capture this occultation event. The light from the moon made the image quality quite low but good enough to gather the data from it.
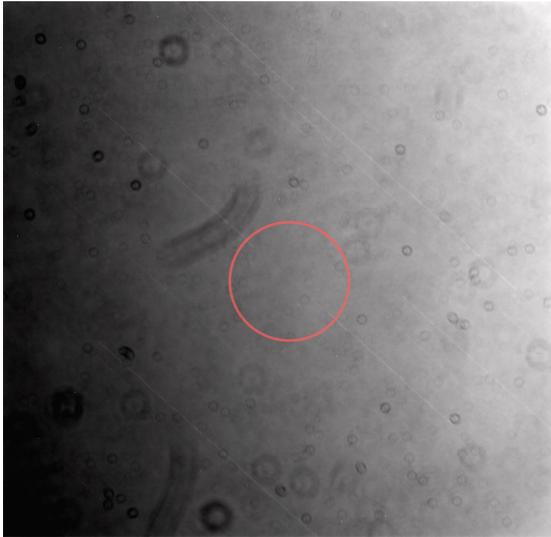

Fig. 3. Occultation of Europa on Aug. 23 2018. The occultation of the star can be seen inside the red circle.

X. REFERENCES

1. *Astrometry.* (2018, July 14). Retrieved August 18, 2018 from https//en.wikipedia.org/wiki/Astrometry
2. Hiltner, William A. *Astronomical Techniques (Volume II of Stars and Stellar Systems).* University of Chicago Press, 1969.