Precision Asteroid Astrometry

Refining Positions of Occultation Asteroids for Optical Navigation

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Abstract— **Among the methods used to guide spacecraft to their destinations, Optical Navigation (OpNav) remains an effective option. OpNav makes use of star fields and small body ephemerides to precisely locate spacecraft. To facilitate accurate OpNav, the small body ephemerides must be constantly updated; asteroid orbits accumulate errors each year of a few milliarcseconds. Through extended exposures, taken with strategic offsets, a least-squares solution can be found that determines updated ephemeris data. This updated data can also be used by occultation astronomers to gain further information about the small bodies, including their size and shape.**

Using the 24-inch telescope at the Caltech Table Mountain Observatory (TMO), we capture two or more 180 second exposures of each target. These images, combined with a file for the predicted background star field and two reference files, are then processed through a series of scripts and programs. Starting with a prediction file and two to five exposures of the asteroid, the data is processed. This original data is about 32MB per observation. Once the data are reduced to only Right Ascension and Declination for each target, the data are ready for delivery. This consists of text only, and for each target takes about 80 bytes; this resulting data reduction is about five orders of magnitude. This method produces observed positions that are refined by about 12 milliarcseconds, a refinement that is accomplished almost nowhere else. The occultation observations that are facilitated by the ephemerides being refined also produce results that are not possible in any other way from ground-based observations.

***Index Terms*—Astrometry, Asteroid, Optical, Navigation, Occultation, Observations, Linux.**

I. Introduction

Astrometry is the process of using astronomical observations to determine the precise magnitude, locations, and motions, of astronomical objects. This project makes use of high precision asteroid astrometry and the related refined ephemerides. These data are then used for precision occultation observations and Optical Navigation (OpNav).

II. Purpose

There are multiple options for spacecraft navigation. Beyond the asteroid belt, radio transmissions have a significant delay between transmission and reception of signal. A round-trip signal to Jupiter will take over an hour, and possibly significantly more depending on the location of Earth and Jupiter at the time. Optical navigation can provide real-time solutions, in the form of onboard OpNav systems, or OpNav may be used because the spacecraft's proximity to a small body may provide an opportunity for more accurate navigation.

Directly imaging asteroids requires nearby spacecraft. To obtain detailed information about them from Earth, astrometry and occultation observations are used. The resulting data produce a silhouette from multiple occultation observations that is superior to other ground-based methods of asteroid characterization.

III. Equipment

Predictions for our observations are made using a program on a Linux machine at JPL; this is the same machine used for remote data reduction. The primary workstation is another Linux computer located in TM-27 at TMO. The observations are made using a 24-inch Ritchey Chretien telescope on an Astro Mechanics mount and located in TM-12 at TMO. The telescope has a Finger Lakes Instrumentation camera with a 4096x4096 pixel CCD. The camera uses a Thermo Cube solid-state cooling system. All telescope operations are controlled using a Windows computer located in TM-12 at TMO, or remotely from JPL. Telescope operation utilizes a suite of off-the-shelf and custom software working in conjunction. Data reduction uses a series of programs and proprietary scripts.

IV. Method

The process for producing refined ephemerides involves three main steps. First, the targets of observation are chosen based on the ability to produce quality images, and pointing offsets are chosen to maximize the number of reference stars in the background star field. Next, the observation process is done either using the equipment at Table Mountain directly, in person, or by accessing the system remotely from JPL. Once all the data for the night have been captured, the files are moved to the primary workstation for data reduction, which is the last step of the process. Finally, the data are ready for delivery to the Minor Planet Center (MPC), International Occultation Timing Association (IOTA) and other interested parties.

A. Preparation

The process of preparing for observations primarily consists of choosing asteroids and other small bodies that present opportunities for good images, and which can be used soon for either navigation or occultation observations. The process begins with a list of objects of interest, mostly asteroids which will be occulting a star before the end of the year. Each potential target is reviewed for suitability. Some won't do. Those that are appropriate are then organized in the order that their images will be made.

The IOTA maintains a list of occultation predictions. This is used as a master list of potential targets, and other objects of interest are added as appropriate. This list is filtered through a series of scripts and programs to produce the predictions that are used for the observation runs. First, the list is reviewed to eliminate targets whose occultation opportunities have already passed for the year. This information is used to choose the files accessed for the predictions. Once the date range for the observation period is chosen, an UPDATE script is used to set the date range. Using a program called GHOSTVIEW, the prediction files are accessed and reviewed.

There are multiple considerations for the predictions, and each has a range of acceptable values for a good target. The three primary aspects of the predictions that are reviewed are the Right Ascension (R.A.), the Declination (Dec), and the number of stars predicted to be near the target. The R.A. must be considered because it represents the sidereal time when the target is at the meridian. On average, about half the targets will not be reasonable because they are only above the horizon during the day. Images may be made of targets that are up to about 2 hours away, plus or minus, from the meridian. The effect of twilight pushes the viewing window just inside of true sunset and sunrise, effectively reducing the number of reasonable targets. Additionally, declination must be considered because the telescope cannot take images through the ground, nor even relatively close to the horizon, due to the amount of atmospheric distortion at that angle. The level of atmospheric distortion is proportional to the "sec (Z)" value, and is related to the angle between the pointing and the zenith. Finally, there must be a minimum number of stars to reference in the image to produce good results. About a couple dozen stars, including those captured by the offsets from multiple exposures, is usually sufficient.

As a target prediction is verified as acceptable, it is marked within the program, and the marked predictions are printed out as hard copies. Additionally, one well-known target with many reference stars is chosen as a calibration field; five exposures of the calibration field will be taken. Due to the way predictions are processed, the targets for all the days are mixed together, so the next step is to sort them by the day they will be taken. Each day is then organized in order of R.A., to facilitate efficient observations in the order that the asteroids approach the meridian. The final step of preparation is to choose image offsets and write them on each hard copy. Targets with fewer reference stars will require more images, and two to four offset values are chosen, using a transparency overlay to determine the most opportunistic values, which capture the most reference stars with the smallest offset. A small offset is beneficial because it requires less movement by the telescope and dome, minimizing the potential for idle time. Offsets are usually 5-15 seconds of R.A. and 1-2 minutes of declination. While the offsets are technically part of the preparation stage, this step is usually completed simultaneously with the observations, allowing one person to control the telescope while another calculates the offsets.

B. OBSERVATIONS

During observation runs, there is a distinct series of steps that must be followed to capture useful data, and to ensure efficient data reduction. While at the observatory, certain text files must be created and maintained for the reduction scripts to work. Additionally, the images and files made must be transferred to the proper workstation for the data reduction process to be done. Each night, before returning to the dormitory to sleep, the final step is to ensure that the initial master script is started, so there will be less downtime later.

There are two text files to be created to guide the Linux scripts that are used for data reduction. The first is referred to as the point file, and contains specific R.A. and Dec values for each exposure taken. Additionally, each line includes the prefix for the target, to associate the images and targets properly. This prefix is also used as the beginning of the image file names, and is included in each line of the other text file. The second text file is referred to as the "temp" file and includes weather information, with one line for each target, regardless of the number of exposures taken. In addition to the target prefix on each line, there are also temperature, pressure, and humidity values recorded at the time of the first exposure. These values are obtained from tmf.jpl.nasa.gov and represent real-time, local measurements at the Table Mountain Facility. The weather conditions are accounted for to derive uncertainties of measured positions. Precision and accuracy are very important. The text files cannot have extraneous lines or spaces, and typos can prevent the master script from even starting. Point file entry count and the total number of exposures must match exactly.

Once the sun rises, quality images can no longer be made. The telescope must be stowed, and the dome must be closed and stored in its "home" location. During the shutdown process for the equipment, the image and text files are transferred to the main workstation. Once the Observer's Log has been filled out, the observation period is done. Before retiring for the night/day, the master script must be run. While onsite at Table Mountain, the main workstation can be accessed directly; this same computer is accessed remotely from JPL the remainder of the time. Successfully running the master script, DOIT, signals the end of the night and the beginning of the data reduction process.

C. DATA REDUCTION

If no problems are encountered, only three scripts and very little effort are required to process the data reduction, but problems are always encountered. The master script can initially encounter typos within the text files, and may not even run. There is also the possibility of typos in those files which will allow this script to complete, but will produce erroneous results. There are also multiple possibilities for issues to arise with the images directly, preventing the scripts from working as intended. In each of these cases, there is a specific process to identify and remedy the problem.

The master script, DOIT, references many subscripts, and uses four primary files and file sets. These are the images, the prediction files, and the two text files: point and temp. During the process of the script, the images are reformatted and renamed, the centers of the targets are attempted to be found numerically, and an attempt is made to produce the R.A. and Dec of each target. If everything went well during the observations, most of the targets are reduced properly. Due to faint targets and imperfections, some of the targets are usually not. These can be identified by reading the report file that is produced, but there are also two helper scripts that are used to identify problems. The CHECK script will return each target, the number of images, and the number of identified targets. If these numbers don't match the target is flagged. The FINDBAD script returns any object within an image that has a bad residual. By using these two helper scripts, problems are identified, and then remedied.

If the number of predicted and found targets do not match, a program called XROVER is used to adjust the file. This program accesses both the images files and the predicted star field based on the point file. The program produces an overlay based on the prediction, and this overlay is intended to be aligned with each image. When the target is unable to be found, this overlay must be moved manually to match the actual star field image. Once the overlay fits, the target is identified and located. Additional scripts help process this modified version of the file, in place of the default results.

If stars in the image produce bad residuals, they can prevent the scripts from identifying the intended target. This can happen because of an unusually bright star or an unexpected moving object. To eliminate the objects with bad residuals, a file is directly modified to identify objects to be ignored. By modifying one of the input files, the scripts can be instructed to ignore targets, reference stars, or uncatalogued stars. There is a similar procedure to deal with a second moving object, like an unexpected second asteroid. Likewise, if the target is too close to a star, the two can be identified as `PAIRS` and the scripts will be forced to reprocess those objects jointly.

There are more subscripts used in the data reduction, but they all lead to the same desired result. Roughly 100Mb of data per target is reduced by six orders of magnitude, to about 100 bytes. This final data is primarily in the form of R.A. and Dec for each target, with some additional information, in the format preferred by the MPC. Once all targets have been evaluated and the troubleshooting process has been completed, the data is ready for final processing for delivery. The DELIVER script produces a single file which contains all the relevant information. This information is copied directly into an email, and this email is sent to the relevant people. Typical recipients include representatives for the MPC, the IOTA, and the JPL Solar System Dynamics Group. Once the data are delivered, the final "cleanup" script creates a *.tar.gz file containing everything but the images, which are also compressed in the process. Other files are removed. In addition to hard copies of the Observation and Reduction logs, these compressed files are burned to DVD and saved as backup copies.

V. RESULTS

After data delivery, the data are reviewed by the MPC. The MPC publishes the results to their website, and these data are then used by occultation observers to image the occultation using the refined ephemerides for a more accurate prediction of the asteroid's location. Similarly, the data may be used for optical navigation, considering the updated information about the objects' orbits. Given an opportunistic occultation, these data can facilitate high resolution occultation observations. Particularly when there are many observers, the resulting observations produce a combination of occultation lines.

The line formed by the star, while the star field is in relative motion, is broken by the occultation. Observations from different locations produce unique lines, and when put together they can form a silhouette of the asteroid, revealing size and shape information in a way that can only be improved upon by direct observation from a passing spacecraft. This effect can be seen in Figure 1. On 19 July 2011, observers in the San Francisco Bay area had the opportunity to image an occultation by Antiope, a binary double asteroid. The results of this type of observation are clearly visible, as the higher the number of observations, the higher the resolution of the resulting silhouette. For OpNav, the same program used during the prediction stage would be used by the spacecraft to determine its location based on the relative locations of asteroids, and other bodies, against the known star field.

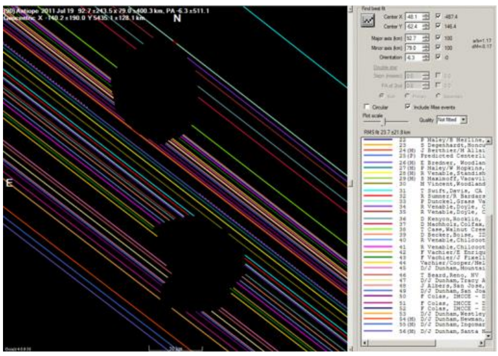

Fig. 1. Example of an asteroid occultation observation. Antiope (binary), 19 July 2011, visible from the San Francisco Bay area.

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