LaBorde
Christopher
Jet Propulsion Laboratory
Intern- Optical Navigation
392L
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Photographing and Determining Accurate Positions of Asteroids in the Solar System through Observational Astronomy and Astrometric Methods

Abstract:

The goal of our work is to update the current positional information of Asteroids in the Solar System. We achieve this objective by taking photographs of known celestial objects in motion and running the photographs through a program which returns precise data on their positions in the solar system. We send these results to the Minor Planet Center (MPC), which keeps a database of the objects and their positions. Other organizations can then access this information through the MPC to further utilize and process it.

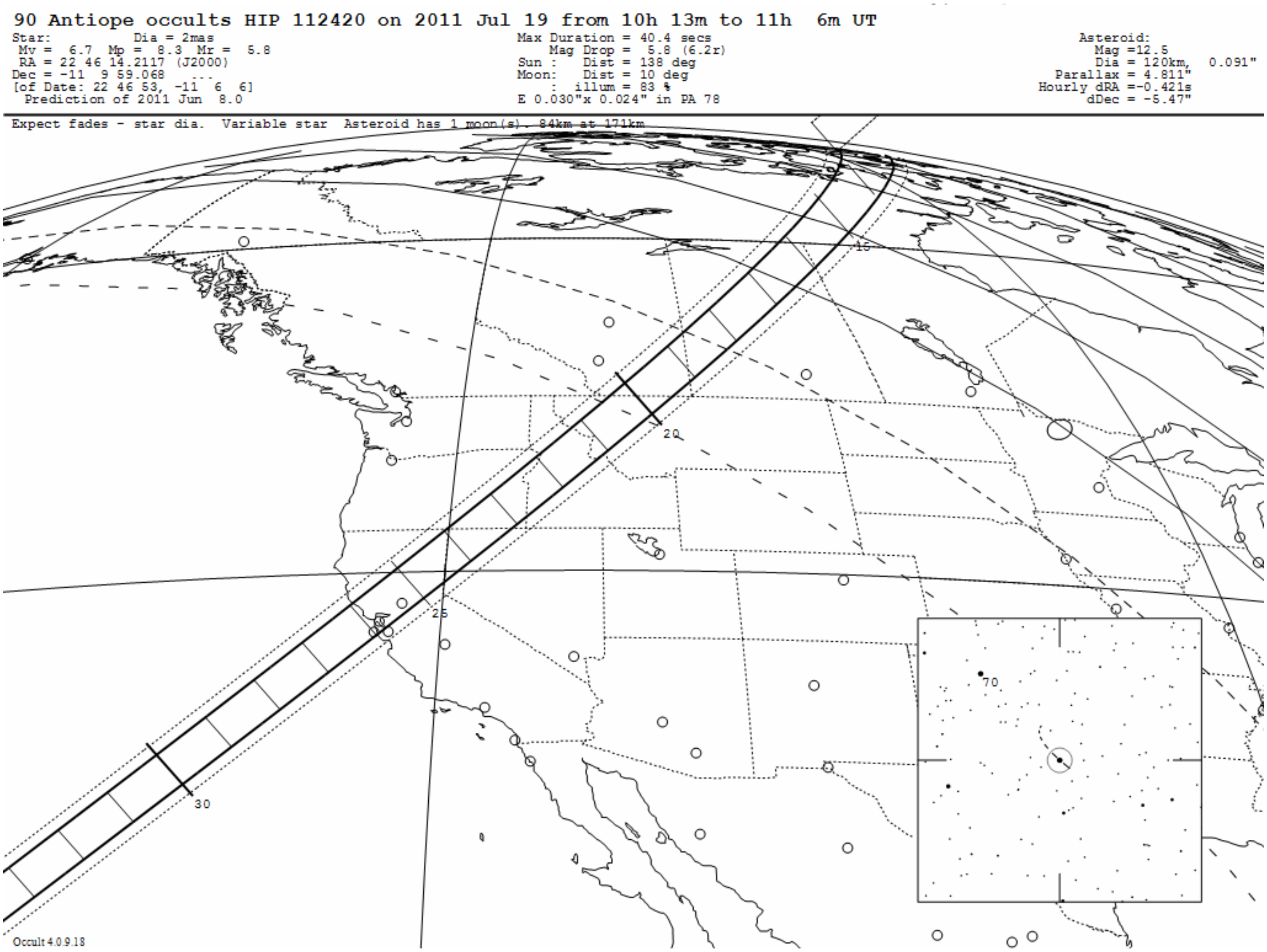
This work is being carried out by Christopher K. LaBorde, Alex G. Carr, and Mary Konopliv under the guidance and direction of Dr. William Owen at the Jet Propulsion Laboratory in Pasadena, California during the Summer of 2016.

This paper will provide some general information on astrometry and our specific role relating to it, as well as describe the techniques we use to collect and analyze this data.

Why on Earth do we want to know where things are?

The gathering of positional information regarding astronomical objects is called astrometry. Study and research in this field is important because it allows us to determine where objects are located in relation to ourselves or other objects in space. This may be useful for example, in monitoring the course of a potentially dangerous asteroid in the vicinity of Earth, or for calculating the correct trajectory for a spacecraft to reach another planet, perhaps to gather resources, reconnoiter, or seed a colony. The study and development of Astrometric techniques also allows us to determine the distances to other stars, and to know how fast they are moving in relation to us.

In addition to simply knowing where these bodies are in relation to us, a major result of these updated positions is the calculation of “Occultation Paths”, paths along the surface of the earth in which a person's view of a star will be blocked for some amount of time by an asteroid passing in front of it. By receiving data gathered during these events and with enough coordination, we can obtain valuable information on an asteroid's size and orientation.



An occultation path of the star HIP 112420 by the asteroid Antiope shown on a projection of the globe. Our work aids in refining the error bounds of this occultation path.

Who Developed this process?

The process that we implement is one that has been refined and tested for decades. It was developed by Bill Owen and his colleagues under the Optical Navigation group at Jet Propulsion Laboratory in Pasadena, California. The programs that we utilize have been used to analyze visual data from spacecraft operating in deep space such as Galileo (1989), Cassini (1997), Deep Space 1 (1998), and Deep impact (2005), and has been implemented in autonomous navigation systems aboard various spacecraft. The software provides scientists and engineers with updated data which they can use to determine a spacecraft's position as it is approaching a target, or preparing for a near-object trajectory change maneuver. We are now getting to see the effectiveness and robustness of this software ourselves by using it to accurately and precisely determine the positions of asteroids.

What do we do?

Imagine a rock the size of New York City barreling towards the earth at a speed of several miles per second. Not a pleasant thought, is it? Although it is a scene played out in countless science-fiction movies, the possibility of this event is quite real. Remember the dinosaurs? Anyone seen one lately?The results that come out of this work aid in the prevention of an event like the one described above, and help us to know where these rocks are and where they are going.

We record positional data regarding asteroids in the Solar System in order to update the catalogs with accurate positional information regarding these objects. Over Centuries, many asteroids have been observed and cataloged. We have a fairly accurate understanding of where many of these objects are. However, our goal is to get precise and highly accurate readings of where they are, thus requiring that we revisit them. It is a process that involves many steps. We record the data in the form of celestial photographs, and then run an analytical software program to precisely calculate where the asteroid is, relative to the center of mass of the solar system, or the barycenter. The software for this process has already been written; our assignments are more on the operations side of the data collecting and processing.

To ensure that our data are as accurate as possible, it is necessary that we optimize our conditions of observation. This means that the muggy, smoggy skies of the Los Angeles Basin are a no-go. Yet, since we are Los Angeles-based, we cannot go so far that it would be impractical. To collect the data, we are placed in control of a ~0.6m (24 inch) telescope located at the Table Mountain Observatory in the San Gabriel Mountains, located near the mountain town of Wrightwood. The observatory is at roughly 7500 ft in elevation and overlooks the high-desert north of the San Gabriel Mountain range. This telescope can be controlled remotely through a computer, but in order to get the immersive and complete astronomer's experience, we are allotted 3 nights of observing every two weeks, when we actually get to travel onsite to the telescope, and reside at the facilities.

How do we do it?

In order to get useful and processable data, targets need to be chosen that will return data with the least amount of error. A program *TGP*, short for Trajectory Geometry Program, consults an ephemeris, or database which contains predicted coordinates for different asteroids for the nights on which we will be observing. TGP also grabs the coordinates of surrounding stars from a star catalog and plots them in relation to the asteroid. Through another program called Ghostview, we are able to see where an asteroid should be on any given night along with the predicted field-of-view of the camera, and to determine whether its position is conducive to data collection by our method.

To determine the quality of the data, several different criterion are considered. We seek to minimize the amount of atmosphere we look through to observe the object – the more atmosphere between us and the star, the more distortion there is to the light due to the diffraction by moving molecules in the air. The closer to the horizon a target is, the more atmosphere we must look through to see it, and the larger the effects of atmospheric distortion. We prioritize targets with numerous stars around the predicted field of view of the camera. The more background stars there are to reference in the set, the more data points there are to contribute to the calculations, and the more accurate the result will be. Asteroids that are near very bright objects are less likely to be considered as viable targets. For example, a target predicted to be near the moon is not a strong candidate, because the light from the moon will wash out any chances the program has of sweeping up the asteroid.

We pick roughly 60 targets per night, taking 2-3 pictures of each target. This is enough work to fill 8:30 pm ~ 5:00am with exposure-taking, roughly sunset to sunrise, which as we know are optimal observing hours for optical astronomers.

For each exposure, we slightly offset the pointing of the telescope to include in the field of view some of the stars outside the periphery of the original prediction. We take multiple exposures with the offset pointings, and reduce the data as a set.

Once the targets are picked and the nights at the observatory reserved, it is time to begin making observations. As night falls, the process of observing is prepared for. The air conditioner in the dome, previously set to the predicted nighttime temperature, is turned off. Since materials expand or contract with thermal changes, our goal is to make the temperature change as small as possible, so as not to warp any of the components.

The telescope that we use is a Astro Mechanics Ritchey-Chretien reflector telescope with an aperture of 0.6m, on an off-axis German equatorial mount.

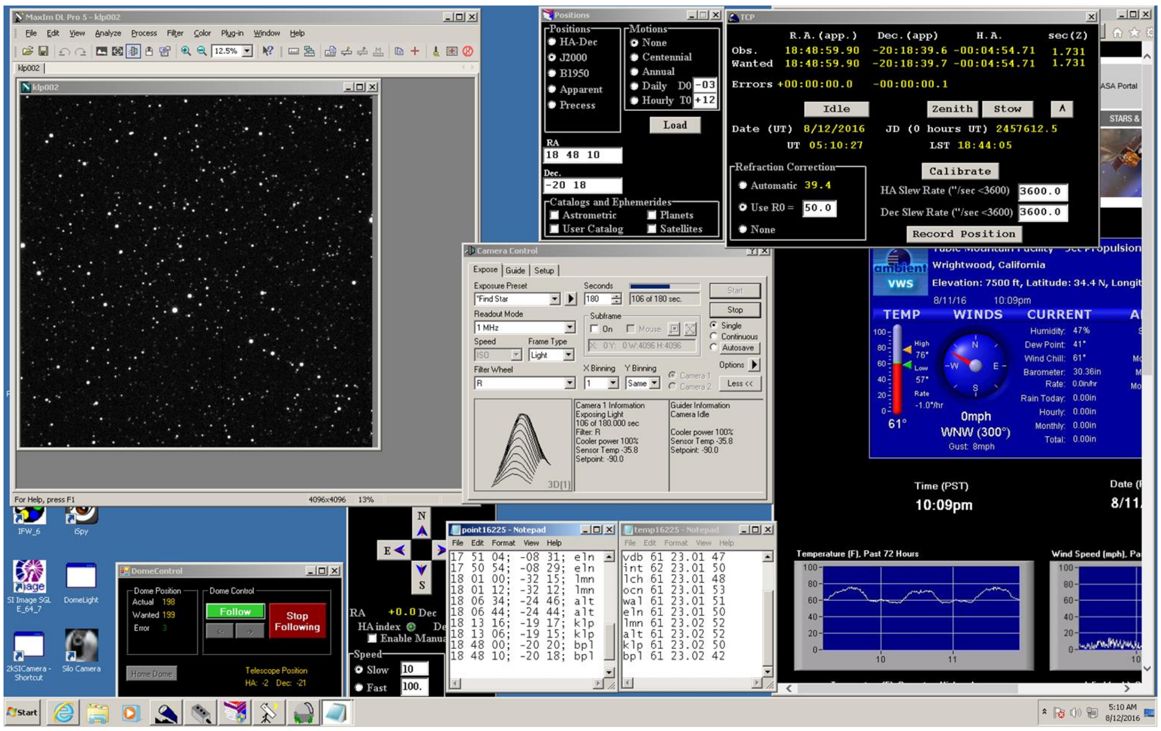
On the computer, the camera which is mounted on the telescope where the eyepiece would be is turned on, as well as the cooler which controls the temperature of the CCD or Charge-Coupled Device. This is important because the CCD produces a substantial amount of heat. Without a cooler, the heat from the CCD would interfere with the readings from the CCD itself – the “noise” from the instrument would disturb the signal that the instrument is trying to detect! The CCD takes the physical light signal and translates it into a digital image. The data in this image is what we run through the analysis program to pinpoint the location of the asteroid, using the star field in the background as an indication of our perspective.

Next, the program which controls the direction of the dome shutter is opened, along with the dome shutter, and the dome is set to follow the pointing of the telescope. The telescope control program which manages control of the telescope is opened, TCP for short, as well as the position client which allows us to feed desired pointings to the telescope. The program that controls the focusing of the telescope is opened, and the coordinates of a star near the zenith are loaded into the position client. Pictures are taken of this star, and adjustments are made according to the focus in order to adjust the focus to prime. These adjustments are made through a program that controls an actuator which varies the position of the secondary mirror. During the focusing procedure, we also calibrate the pointing of the telescope to reflect as accurately as possible the coordinates which we have given it. This is through a program which allows one to incrementally adjust the pointing of the telescope, named the “Paddle” client. The position, focusing, and paddle clients are C++ programs that relay information to the TCP. Next the website that provides local temperature, pressure, and humidity readings is opened, as well as two text files in which the same data and the pointing of the telescope are recorded for each exposure taken. The TPH readings are used in a final analysis to calculate a distortion coefficient, a parameter that modifies an error bound for the final position reading. Once this has been done, the pointing coordinates for the first exposure are loaded, the filter set to “R” for red light, the exposure time set to 180 seconds, the readout set to 1MHz, and shoot.

As pictures are taken there are a couple of tasks that must be completed. There is an observation log that must be updated with each exposure. The “prefix” of the target, which is really a condensed 2-3 character string unique to each target is recorded. We record the temperature, pressure, and humidity readings at the time of the exposure and the time of which it started adjusted to Universal Time

Standard (UTC). We record the Right Ascension and Declination pointing coordinates of the telescope and the hour-angle, or the amount of time the pointing is off of the local meridian. Finally we record the value of secant z, or a calculation of the number of atmospheres we are looking through. A pointing

directly at our zenith would give a secant z of 1 atm; the pointings generally return a value for secant z between 1.00 and 3.00, and anything above roughly 2.8 is questionable. We then input the temperature, pressure, and humidity readings into one of the text files, input the pointing in the other, preload the coordinates for the next shot, and save the previous picture. We have 180 seconds to complete all of this. We do this until the targets are exhausted or the sky gets too light to gather any more data. After our pictures are complete, we send the data to another computer at TMO that we can access remotely from JPL, and reduce the data to see what we've got.



The majority of the programs we use during observing to operate the telescope. Including: TCP, Paddle, Dome Control, Position, Camera clients

Data Reduction

After having transferred the files over to Dubhe, we run a script called “Doit”. This script is a kind of “Master script” that calls upon several other lower-level scripts to organize and interpret the data. The script renames and reformats the picture files, finds the central point of each image present in the pictures, and runs the calculations to determine the right ascension and declination, or celestial coordinates of each of the targets in the pictures. One of the scripts involved will actually match known coordinates of catalogued stars to the background stars in the pictures, providing an accurate estimation of exactly where the telescope was pointing at the time of the exposure.

Next, we run a script called “Report” which provides a detailed summary of the results, sourced from the output files produced by some of the lower-level scripts in “Doit”. The report script provides the “seeing” for the pictures taken, or the quality of the observation during the shooting of the target. The worse the seeing is, the higher the range of uncertainty. The script also provides the number of images of targets, reference stars, and uncatalogued stars, the number of pictures processed, and the number of pictures in which the targets were found. The script also provides the residuals of the reduction. This is the difference between the predicted position of the target and the observed position of the target.

We call upon a script called “findbad” which presents us with the targets that have returned bad residuals. These can be caused by interference by bright objects close to an image and are swept up in the reduction program as being part of the image. When this happens, we can go into the input files of the scripts and manually delete the image, telling the program not to consider that image during the processing, and run the program again.

Once the reduction has been checked, any hiccups have been investigated and the data has been deemed ready for submission, we run the “Deliver” script. The script gathers the results of the reduction from all of the targets, and compiles them into a single file. We enter our names as the Observers and gatherers of the data, and send the file off to the Minor Planet Society for the data to be verified, and the ephemerides to be updated.

Challenges

The work that we perform is not without it's challenges. There is a variety of practical, human, and logistical challenges that can arise over the course of the entire process of gathering and reducing the data. Since we are relatively new to the process there is a learning-curve that presents itself. Whenever a problem shows itself for the first time, a more experienced senior must be consulted, as to make sure that the correct mitigation process is followed. For example, sometimes the TCP client will glitch, and will load an erroneous value into the direction to which the Telescope will aim. This occurred once this summer and loaded a value of 300,000 into the declination input. Note that our normal range for declination falls between +30 and -30. This caused the Telescope to attempt to achieve a position of 300,000 for its declination, a value far beyond the limits of the hardware. Luckily a Hard-limit switch had been installed previously, and caused the moving motors of the telescope to turn off, preventing the destruction of many instruments attached to the telescope.

A general unfamiliarity with Linux operating systems and control of the computer through command prompts also proved to make the data reduction and navigation of the environment ponderous, but with time, the system became more familiar and was easier to use.

Being that humans were operating this machine in direct conflict with their circadian rhythms also was a considerable contributor to error. Staying up from Dusk until the morning light and repeating a menial yet important task throughout that entire span was not the most conducive to

allowing one to stay alert. Coffee and Late afternoon naps were an effective strategy to combat these ailments.

The largest variable outside of our control was most likely that of the climate. In order to obtain usable information in the form of photographs of the stars, one must be able to see them. During the summer months, weather systems will sometimes direct humidity over the locality, producing clouds that are not the easiest to see through. Whenever the weather did not allow for proper observing, the night was called off and we were forced to wait in earnest for the next evening.

However, despite all of these challenges, the conditions were generally good enough to obtain reliable, accurate data.

Support Acknowledgements:

Without a team managing logistics and operations, this work would not be possible. We are lucky to be on one with an extensive collection of experience surrounding these operations.

This project is headed by Dr. William Owen, who is the head of the Optical Navigation team at JPL. He is an expert in his field, and looking at the scrutiny and the detail that has gone into the development of this methodology, it is no surprise that he is considered one of the best in the world in optical navigation.

There are many other roles that support us including the lead astronomer at Table Mountain, Heath Rhodes, and the Security, Administrative, and Hardware Production teams at the facility. Heath has earned his tenure over the last two decades and can be declared a veritable wizard in software, hardware, and project management at Table Mountain. The cooperation and involvement of all of these parties is what allows this operation to run; without them, this work would not be possible.

We will count the project's success by the continuing and consistent accurate calculations of asteroids' positions in the Solar System. Until this point, that goal has been achieved. Mission Success.

<u>Sites referenced:</u>

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