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The Taiwan-America Occultation Survey for Kuiper Belt Objects

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Abstract. The purpose of the TAOS project is to directly measure the number of Kuiper Belt Objects (KBOs) down to the typical size of cometary nuclei (a few km). In contrast to the direct detection of reflected light from a KBO by a large telescope where its brightness falls off roughly as the fourth power of its distance to the sun, an occultation survey relies on the light from the background stars thus is much less sensitive to that distance. The probability of such occultation events is so low that we will need to conduct 100 billion measurements per year in order to detect the ten to four thousand occultation events expected. Three small (20 inch), fast (f/1.9), wide-field (3 square degrees) robotic telescopes, equipped with a 2,048 × 2,048 CCD camera, are being deployed in central Taiwan. They will automatically monitor 3,000 stars every clear night for several years and operate in a coincidence mode so that the sequence and timing of a possible occultation event can be distinguished from false alarms. More telescopes on a north-south baseline so as to measure the size of an occultating KBO may be later added into the telescope array. We also anticipate a lot of byproducts on stellar astronomy based on the large amount (10,000 giga-bytes/year) of photometry data to be generated by TAOS.

1. Introduction

More than three hundred small planetary bodies with radii larger than 100 km have been detected beyond Neptune using large telescopes, since the discovery of 1992 QB_1 (Jewitt & Luu 1993) eight years ago. Pluto and its satellite Charon are probably the largest members of this family, the so called "Kuiper Belt Objects" (Edgeworth 1949; Kuiper 1951), which is believed to be the source of most short period comets that return to the inner solar system every few years.

In general, a region close to Neptune is dominated by the gravitational perturbation of this giant planet. Hence, a depletion from a smooth extrapolation of

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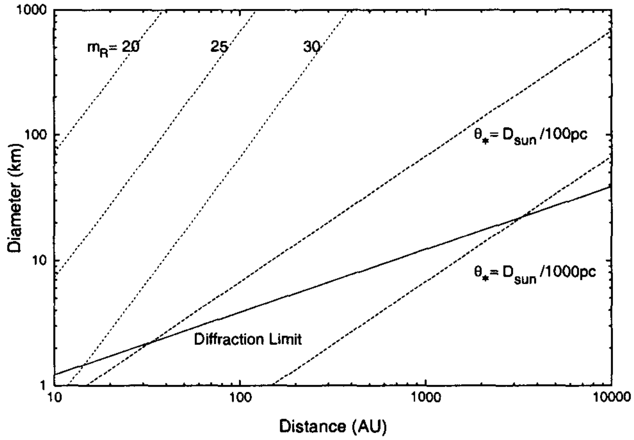

Figure 1. The minimum size of an object at a given distance that can be detected by an occultation survey is determined by the combinational effect of diffraction (solid line) and the finite angular size of the target star (long dash lines). Roughly speaking, an object located above these lines can be detected. On the other hand, the detection limit of a direct detection, which depends on the light reflected from an object, is shown as short dashed lines with a red magnitude of 20, 25 and, 30 respectively. Here, an albedo of 0.04 is assumed.

the surface density of the planetary system is expected (Weidenschilling 1977). In a more distant region, the gravitational influence of Neptune and the giant planets should be insignificant. However, observations indicate a further depletion for large objects beyond 50 AU (Allen & Bernstein 2000). An alternative study of this region is demanded.

TAOS (Taiwan America Occultation Survey) is a joint project among Lawrence Livermore National Laboratory (through its Institute of Geophysics and Planetary Physics), National Central University (Institute of Astronomy), and Academia Sinica (Institute of Earth Sciences and Institute of Astronomy and Astrophysics). The purpose of this project is to directly measure the number of these KBOs down to the typical size of cometary nuclei (a few km). This knowledge will help us understand the formation and evolution of comets in the early solar system as well as to estimate the likelihood of their impacting our home planet.

2. The Strategy

Moving in between the earth and a distant star, a KBO will block the starlight momentarily. A telescope monitoring the starlight will thus see it blinking. In contrast to direct detection of reflected light from a KBO by a large telescope where its brightness falls off as roughly the fourth power of its distance to the sun, an occultation survey (Bailey 1976; Dyson 1992; Cook et al. 1995) relies on the light from the background stars thus is much less sensitive to this distance.

The detection limit of an occultation survey is determined by the diffraction effect and the angular size of the target star. These are shown in Figure 1. That limit would be mostly set by diffraction for sun-like background stars located at 1,000 pc (m $\sim$ 15). It is obvious that occultation is a superior method for the detection of comet size objects beyond Neptune. As for the diffraction itself, though, the size of a KBO, s, is small compared to its distance, r, from us, $s^2/(\lambda r)$ could be larger than unity. Thus, Fresnel diffraction applies.

Our design goal is the capability to measure a rate of stellar occultations by comets of 1 per 1,000 stars per year of observing time. The typical relative velocity between a KBO and an observer is around 20 km/s. For a 3-km comet an expected duration of 0.2 seconds follows. Hence, there are approximately (3,000 stars)$\times$(10% $\times 3 \times 10^7$ sec)/(0.2 sec) $\sim 10^{11}$ photometric measurements per year, from which we want to derive less than one spurious occultation. The "false alarm" probability per observation must therefore be exceedingly small if the results of the experiment are to be interpreted with confidence. False alarms can arise from a variety of causes, a major one being the Poisson statistical fluctuation in the number of photons detected from a light source of constant intensity. False alarms due to this can be controlled only by detecting a sufficiently large average number of photons from a star. This clearly sets the brightness limit of the target stars, and hence the telescope aperture required. Extreme atmospheric fluctuations may also pose a threat of false alarms. In addition, false alarms can occur when a star is occulted by terrestrial objects, such as insects, birds, bats, aircraft, and even orbital debris. In practice, birds and swarms of insects appear to be the most damaging sources due to their potentially great numbers, whereas orbital debris can be neglected due to the short time scale (less than 10^{-3} s) of any occultation event. We require from our system a false alarm probability per measurement of $\sim 10^{-12}$, resulting in a false alarm probability per year of approximately 0.1. A combination of at least three telescopes monitoring the same fields at the same time was proposed.

Table 1. This is an estimate of TAOS event rate. r is KBO's distance to the sun. $\Sigma(r)$ is the surface density of the solar nebula. s is the diameter of a KBO.

r (AU)	$30 \sim 50$	$50 \sim 100$	Note
condensible mass	24 $M_\oplus$	44 $M_\oplus$	minimum solar nebula $\Sigma(r) \propto r^{-1.5}$
event/year	1200	420	size distribution: $dN \propto s^{-3.5}$
$\times$ 1/100	12	(not depleted ?)	depletion due to Neptune

Using an initial solar nebula model (Hayashi 1981, 1985) considering its condensible parts (Weidenschilling 1977; Pollack 1996; Jewitt 1999) and an assumption of the size distribution of KBOs, we may obtain an estimate of the occultation events that could happen at a specific site with a few observational constraints. An example is shown in Table 1. A depletion of 100 times within 30 to 50 AU is expected. However, a higher rate from the outer region is possible if there is no depletion due to the gravitational perturbation of the Neptune, for example. Other assumptions are: the number of target stars per field (3,000), duty cycle in a year of observation (10%), disk thickness ($\pm 20°$), phase angle of KBO (at opposition), mass density of a KBO (1 g/cm^3), and wavelength of observation (500 nm). One should note that the event rate listed in Table 1 is somewhat different from the expected detection rate. The latter depends on the site conditions, various noises from hardware, and our photometric algorithm. Nevertheless as serious as the issue is, it is beyond the scope of this brief report.

The probability of such occultation events is so low that we will need to conduct 100 billion measurements per year in order to detect the ten to a few thousand occultation events expected. The large range in this estimate reflects our ignorance in how to extrapolate from large KBOs to small ones. Evidently, there is an urgent need to conduct a census. An occultation survey seems to be the only way to tell if an outer edge of the solar system is observed. Thus, instead of doing a "pencil-beam survey" with large telescopes for several days a year, we use small telescopes to constantly monitor with wide fields a sufficient number of target stars. This fully robotic system including its real-time control, analyzing software, and large data archive handling capacity only has recently become technically feasible.

Though, a larger object has a better chance of occulting a distant star, an analysis of the occultation duration shows that most of the events are due to small comet-size objects. Chiang & Brown (1999) observations yielded $dN \propto s^{-3.6}$. There could be thousand times more events from objects of one tenth of their size if a size distribution of $dN \propto s^{-4}$ (Kenyon & Luu 1999) is assumed. Thus, a long occultation will be a very rare event which is worth follow-up observations with large telescopes. Grazing events will reduce the detection rate further. For spherical objects with a size cut-off and a size distribution given above, up to 40% of the events might be lost as being too short to be detectable.

3. The Project

Three small (20 inch) fast (f/1.9) wide-field (3 square degrees) robotic telescopes, each equipped with a 2,048 $\times$ 2,048 CCD camera, will be deployed along a 7 km east-west baseline. They will operate in a coincidence mode so that the sequence and timing of the three separate blinkings can be used to distinguish real events from false alarms. The three partners will each contribute one telescope and work together to set up the automatic observatory on peaks at 3,000 m elevation in or near the Yu-Shan (Jade Mountain) National Park in Taiwan. The three robotic telescopes will automatically monitor 3,000 stars every clear night for several years, consult among themselves to reject false events, and notify us via telecommunication when a possible event is found. For each telescope, a weather station is integrated with the robotic enclosure which can be shut down during a power failure.

All telescopes shall monitor the same field at the same time. The selection of star fields for an occultation survey is subjected to the following factors. First of all, photometry is a concern. The performance of the optical system, electronics, and the site set a limit on the magnitude of the target stars. Simulation and on-site testing are needed in order to determine a realistic value. A star too bright should be avoided as well as the moon light. The second is to have the density of target stars high enough so that one could have a reasonable event

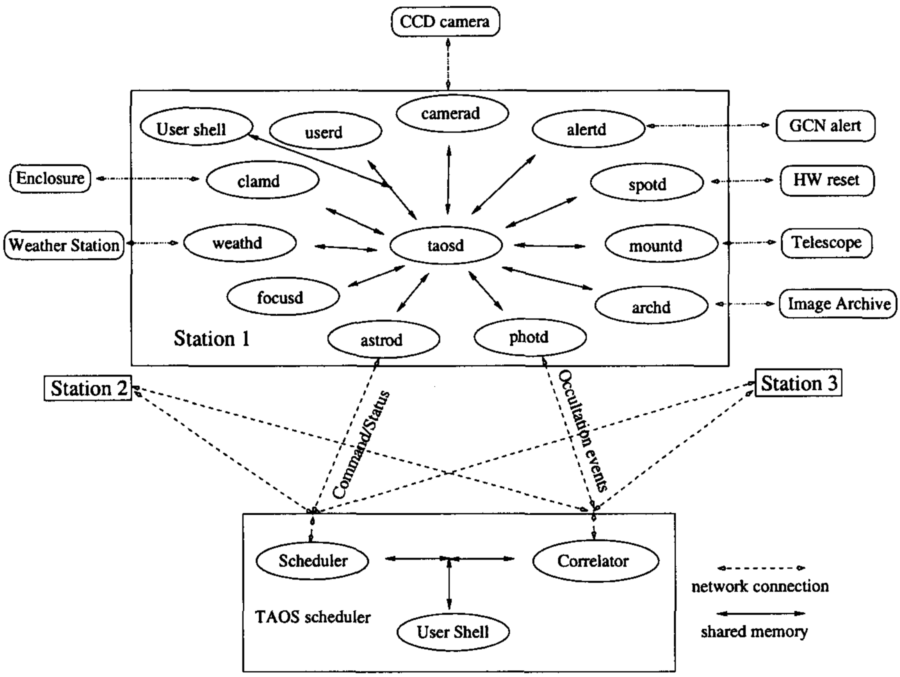

Figure 2. TAOS software scheme

rate. A number density around 800 to 1,300 stars per square degree might serve this purpose. To have a higher probability of occultation, one looks for an event near the ecliptic plane and near the opposition position. Other criteria such as a request to search for a possible Neptune Trojan, to conduct a survey away from the plane to understand the inclination distribution, or, to distinguish a distant KBO from a nearby asteroid might also affect the selection of the observing field.

To spot an occultation event, one straightforward solution is to operate in "drift mode". This means that after pointing a telescope towards a selected field, the tracking would be turned off so that stars drift across the image frame from east to west at the sidereal rate. Some issues are of concern. For example, re-pointing the telescope on a specific field would be needed. The image motion and a shutter operating on and off at a rate of around $10^5 \sim 10^6$ per year might pose a problem. Aiming at the detection of a 5 Hz signal, a special mode of operation could be helpful. The so called "zipper mode" is now under consideration (Axelrod 1998; Liang 1999). Several versions are possible. The basic idea is to keep tracking at the selected field, but to shift the whole frame electronically a few pixels every 0.2 second. A detailed analysis on the overlapping of a crowded field and other issues are being undertaken.

The control and analysis software is technically the most challenging part of the TAOS project. We tap the experience of LLNL's MACHO project. State of art hardware and software are both certainly necessary. Based on the program structure of ROTSE project, on which one of our collaborators (LLNL) is working, a source code of more than 30,000 lines is anticipated for the LINUX system. Figure 2 shows the basic structure of the TAOS software. A few more features are needed here including a photometry algorithm which is the central part of real-time event analysis, an auto-focusing and data archiving algorithm, and a real-time networking "brain" which correlates events and operates all three telescopes at the same time. These might make up of a program of more than 10,000 lines and integrating and testing will follow.

4. Perspective

The current plan calls for beginning routine observation by the end of the year 2001. All telescopes will be installed at one site at an early stage. The extension of the baseline will be evaluated thereafter. A fourth telescope on a north-south 2 km spur to refine the size information of occulting KBOs is being contemplated. It will help to further reduce the false alarm rate. Follow-up observations using large telescopes at major observatories around the globe attempting to detect the reflected sun light from the KBO, hence its orbit and distance, are being organized. In addition, the capability of reacting to GCN alerts will be implemented as shown in Figure 2. We anticipate a lot of byproducts on stellar astronomy based on the large (10,000 giga-bytes/year) photometry data bank to be generated by TAOS. The monitoring of a few selected fields which contain some other interesting objects is considered. No doubt, with these small telescopes, a project like this could be very fruitful and exciting in the next few years.

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