The TAOS robotic observatory

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ABSTRACT

The Taiwanese-American Occultation survey (TAOS) operate four small telescopes in central Taiwan to search for occultations by small (∼1 km diameter) Kuiper Belt Objects. The system is fully robotic,[1] requiring human intervention only in the event of hardware failures. However, the status of the system during observations is monitored remotely via smart-phone. A successor survey, the Transneptunian Automated Occultation Survey (TAOS II)* is currently being constructed. This next generation survey will be more than one hundred times

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*The name of the successor survey was changed due to the fact that it will be located in Mexico.

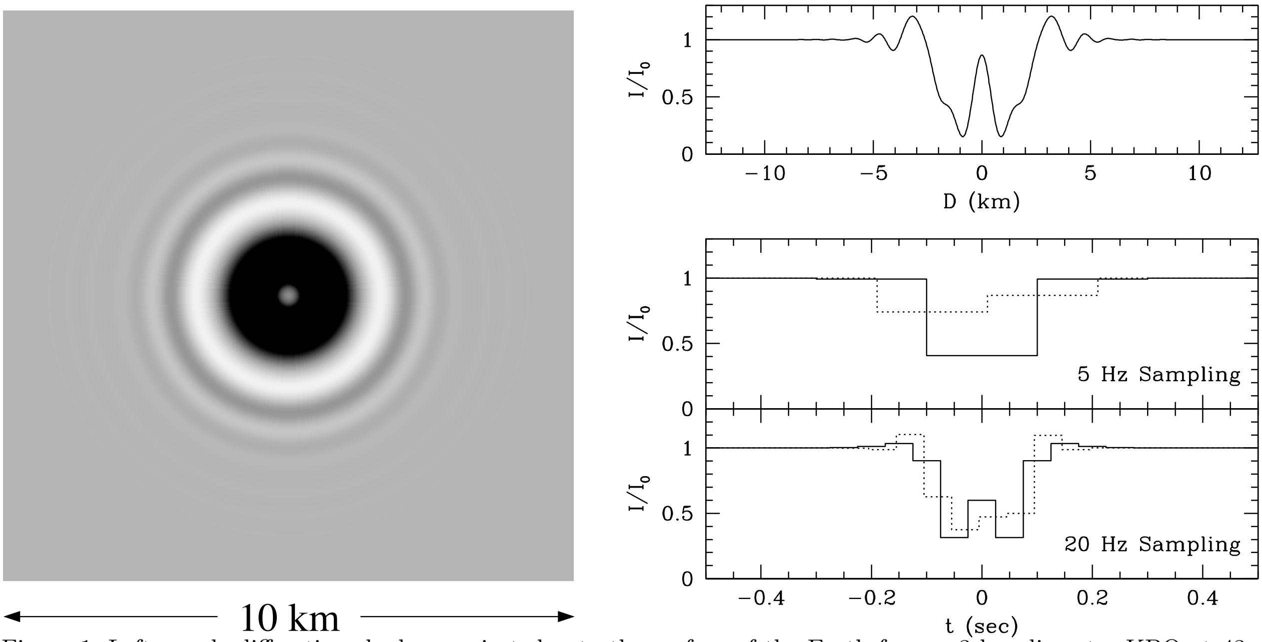

Figure 1. Left panel: diffraction shadow projected onto the surface of the Earth from a 3 km diameter KBO at 43 AU. Right panel top: perfectly sampled lightcurve assuming zero impact parameter. Right panel bottom: same lightcurve as sampled by the TAOS system at 5 Hz and 20 Hz. Solid curves have measurements centered on event, dotted lines shows lightcurves where sampling is out of phase with event.

as sensitive as the earlier survey. In this paper, we summarize the science goals of the surveys, describe the two surveys, and discuss the lessons learned in automating the TAOS observations.

1. SCIENCE GOALS

The TAOS project aims to measure the size distribution of Kuiper Belt Objects (KBOs) with diameters 0.5 km $< D <$ 30 km. Such objects are extremely faint, with typical magnitudes $R > 28$, and are thus undetectable by direct imaging. However, a small KBO will induce a detectable drop in the brightness of a distant star when it passes across the line of sight to the star.[2–12] The goal of the TAOS project is to detect such occultation events.

The primary target population for TAOS is small (∼1 km diameter) KBOs, whose sizes are on the order of the *Fresnel scale*, which is given by

$$F = \sqrt{\frac{\lambda\Delta}{2}},$$

where λ is the wavelength of observation and Δ is the observer–KBO distance. For TAOS, the median wavelength of observation is $\lambda \approx 600$ nm, and the typical distance to KBOs is 43 AU, resulting in $F = 1.4$ km. Occultation events by KBOs with diameters $D \lesssim 10$ km thus show significant diffraction effects. This is illustrated in the left panel of Figure 1, which shows a simulated occultation “shadow” from a 3 km diameter KBO projected onto the surface of the Earth.

The Earth and the occulting object are in relative motion, with the velocity dominated by the reflex motion of the Earth. This induces a variation in the measured stellar flux over time. The timescale of an occultation event is set by the relative velocity between the KBO and observer, the size of the occultation shadow, and the impact parameter (minimum distance between the KBO and the line of sight to the target star). The relative velocity between the Earth and KBO is given by[7]

$$v_{\rm rel} = v_{\rm E}\left[\cos\phi - \left(\frac{1\,{\rm AU}}{\Delta}\right)^{\frac{1}{2}}\left(1 - \frac{1\,{\rm AU}^2}{\Delta^2}\sin^2\phi\right)^{\frac{1}{2}}\right], \quad (1)$$

where ϕ is the angle of observation between the occulted star and opposition, and $v_E = 29.8 \text{ km s}^{-1}$ is the velocity of the Earth around the Sun. The event width (the length of the chord across the occultation shadow where it crosses the telescope) is given by

$$W = \sqrt{H^2 - b^2},$$

where b is the impact parameter, and H is the event cross section, which we define as the diameter of the first Airy ring of the diffraction shadow, and which can be approximated by[7]

$$H \approx \left[(2\sqrt{3}F)^{\frac{3}{2}} + D^{\frac{3}{2}}\right]^{\frac{2}{3}} + \theta_* \Delta, \tag{2}$$

where θ_* is the angular size of the occulted star.

For most of the small objects ($D \lesssim 1$ km) targeted by this survey and target stars with small angular diameters (the vast majority of stars covered by this survey), the minimum event cross section is set by the Fresnel scale:

$$H_{\min} \approx 2\sqrt{3}F. \tag{3}$$

At 43 AU, $H_{\min} \approx 5$ km. At opposition ($\phi = 0$), $v_{\text{rel}} \approx 25 \text{ km s}^{-1}$, and with $b = 0$ the resulting event duration is 200 ms, with the duration getting smaller as b is increased.

Theoretical occultation event lightcurves are shown in the right panels of Figure 1. The top panel shows a slice through the simulated diffraction shadow, assuming the KBO crosses the line of sight to the star ($b = 0$). Note the event width, given by the distance between the two top peaks, is about 5 km. (In this case, the event width is dominated by the Fresnel scale, so the approximation given in Equation 3 applies.) The bottom panels show this event as it would be measured by the TAOS system at 5 Hz and 20 Hz. Given the short time scale of the events, it is necessary that the sampling cadence of the lightcurves must be 5 Hz or greater, otherwise the event signal would be washed out. For TAOS I, we have opted to sample at 5 Hz in order to maximize the number of target stars available to the survey.

2. THE TAOS I ROBOTIC OBSERVATORY

The TAOS I system is described in detail in Ref. 1. The collaboration operates four small telescopes at Lulin Observatory (see Figure 2, left panel) in central Taiwan to search for occultation events by small KBOs. Such occultation events are extremely rare (estimated rates range from 10^{-4} to 10^{-2} events per star per year), and at the 5 Hz observing cadence used by TAOS, they result in measured flux drops of typically $\lesssim$30% in one or two consecutive points. This presents a number of challenges, in particular the identification of false positive events of statistical origin and candidate events which are in fact of terrestrial origin (e.g. birds, airplanes, and extreme scintillation events). We reject these false positive events by requiring simultaneous detection in all of the telescopes.[13]

The four identical telescopes were manufactured by Torus Technologies (see Figure 2, right panel). Each telescope is built with a fast (F/1.9) Cassegrain design, with a 50 cm diameter primary mirror. Each telescope is equipped with a Spectral Instruments camera using an e2v 2048×2052 CCD42-40 imager with 14 μm pixels. The CCD covers a field of view of about 3 □°. To achieve a 5 Hz sampling cadence, we operate the cameras in a custom readout mode we call *zipper mode*. A description of zipper mode is beyond the scope of this paper; see Ref. 1 for details. We plan to replace the cameras in July of 2011 with frame transfer cameras. The cameras are only 1k×1k, so we will lose 75% of our field of view. However, the frame transfer capability allows us to read out full frame at a 10 Hz cadence if we use 2×2 binning. Zipper mode operations will no longer be required, and the resulting improvements in signal-to-noise will increase the number of viewable stars by a factor of two to three, despite the loss of a significant fraction of our field of view.

The primary motivation for automating the survey is the fact that the observing plan of the survey is so simple that it would be inefficient to have an observer on site. TAOS has a list of 167 standard field centers[†]. When the weather is good, the field closest to 45 minutes east of zenith is selected. All four telescopes track the

[†]See http://taos.asiaa.sinica.edu.tw/taosfield/

Figure 2. Left panel: Lulin Observatory. The four TAOS I telescopes are labeled. Right panel: One of the four TAOS I telescopes.

field for 90 minutes, while zipper mode images are collected. This is repeated until dawn or bad weather. A significant software development effort was required to implement synchronous four-telescope imaging at 5 Hz with all of the telescopes centered on the same field. It was then fairly simple to automate the scheduling of observations. The automated scheduler will also respond to Gamma Ray Burst (GRB) alerts from the GRB Coordinates Network,[14] and it has the capability to manually schedule observations ahead of time for any events we would like to follow (such as a predicted asteroid occultation event).

The TAOS I project began collecting data in February 2005. In the subsequent six years of operation, we have found that the three most important pieces of equipment in terms of automated operations are the lids, the weather stations, and the watchdog timer in each of the four observatory control computers. Of these items, only the watchdog timer did not give us any problems. We also had some design problems with our control software. Given their importance for safe operation of a remote observatory, we present our experience with the control software and the aforementioned equipment in the following subsections.

2.1 Watchdog Timer

The TAOS I watchdog timer subsystem is described in detail in Ref. 1. In summary, each telescope enclosure has its own control computer. In each control computer we have installed a 32-bit I/O card, which is connected to an external control box. The 16 output bits on the I/O card control a set of relays to power on and off various pieces of equipment, and the 16 input bits monitor the status of a set of switches, including the limit switches on the telescope and lid. One of the output bits is connected to an ICS Advent WDT5 watchdog module. The output bit must be pulsed at a rate of 1 Hz, otherwise a switch inside the module will open. The output of the module is connected to a series of relays which will automatically cut the power to the telescope and close the lid when the switch in the watchdog module opens. This subsystem thus puts the system into a safe state in the event of a software failure or system crash, because if the control computer dies, there is no way to close the lids remotely. The watchdog timer has been necessary several times over the past few years, usually when a SCSI disk failure caused the computer to crash.

2.2 Lids

The lids (or dome shutters) can be considered the most important piece of any observatory, whether robotic or not, since they are the only components whose failure produces a significant risk of damage to other components inside the observatory enclosure. There are a number of options for reliable lids (Ashdome, or the ROTSE design). However, the TAOS I project had stringent requirements on the structural strength of the lids. Taiwan is subject to several typhoons every summer, and there are often dangerously high wind speeds present at the observatory summit. We therefore opted to use a custom lid design.

Figure 3. Left panel: TAOS I enclosures with original lids. Right panel: same enclosures with new lids.

The original lids used a clamshell design, using two sets of four leaves, one each on the east and west sides of the enclosure (Figure 3, left panel). The lids would open from the top center, and the leaves would nest as the top leaves spread apart. The lids were controlled with a pair of hydraulic jacks on the north and south sides of the enclosures, with a mechanism consisting of a set of gears and lever arms to move the topmost leaves. This design was structurally very sound. However, we had many mechanical problems with the opening and closing mechanism. The leaves would often get stuck, which would result in damage to the gears. Furthermore, instead of remaining tightly closed, the lids would drift open over time, and water would leak through the openings on the top of the lids and drip onto the telescopes. We decided after a short period to use a new design.

The new lid design, currently in use, is a counterweighted monolithic lid which is moved on and off the top of the enclosure with an electric motor and a set of lever arms (see Figure 3, right panel). The lids are made of polyurethane-filled fiberglass and were engineered by the Aeronautical Research Laboratory of the Chungshan Institute of Science and Technology in Taiwan to withstand the most extreme wind conditions. These lids have proved to be very reliable, with only a few minor problems which have been solved. The worst incident occurred when a nearby bush grew too large, got tangled with the counterweight, and broke the weld holding on the counterweight arm. We now regularly trim the vegetation in the immediate vicinity of each enclosure.

2.3 Weather Stations

TAOS I originally used a set of four Davis Vantage Pro weather stations. However, conditions at Lulin Observatory are usually very humid, so most of our observing is done in fairly humid weather. Therefore, accurate measurements of the dew point are required in order to ensure that condensations does not form on the telescopes or associated electronics inside the enclosures. We found that the Davis devices did not accurately measure the dew point when the relative humidity was much above 80%. In fact, we found that the humidity measurements from each of the four weather stations were significantly different at any given time.

After researching the issue, we tried out a Vaisala HMT337 humidity sensor. This device is designed for high humidity applications, and provides an accuracy of $\pm 1.7\%$ in relative humidity (or more importantly, $\pm 0.3^\circ$ C accuracy in the dew point). After testing, we found it worked well and bought a new device for redundancy. After installing the second device at Lulin, we found that once again the dew point measurements were significantly different between the two devices. This was not unexpected since Vaisala recommends that the devices be calibrated every six months, and the device first installed at Lulin had been in operation for over a year. Sending the devices to the manufacturer would be logistically difficult since it would involve shipping overseas, but we found that the Industrial Technology Research Institute in Hsinchu, Taiwan had the necessary equipment for calibration of the humidity sensors. We now schedule recalibration of the two sensors every six months (as recommended by Vaisala), with a three month offset between the two devices so we always have at least one running at any given time. We now find that both devices read the same value within the specified error at any given time.

The devices have proven reliable over several years. However, we have had occasional damage to the serial interfaces on the devices, likely from lightning strikes. We have found that it was in fact a good design to have redundancy in our weather sensors since we did not need to shut down while the damaged sensors were being repaired. Ideally we would have a third set of instruments, so if one of the devices started providing incorrect information, we would have a good idea which one it was. However, we do not currently have plans to install a third sensor at this time.

We also have two Vaisala WXT510 weather stations and four Vaisala DRD11A rain sensors installed at the site. The weather station has the advantage that it uses a set of transponders to measure wind speed rather than a mechanical anemometer. The weather stations also have rain sensors which are not only capable of detecting precipitation, but of measuring the quantity. However, even with the two weather stations and four rain sensors, we still have a significant design flaw in our weather monitor subsystem in that our rain detection surface area is much less that 1% of the combined surface area of the telescopes and electronics inside the enclosures. This ensures that when it does start raining, we likely have quite a bit of rain hitting our equipment before we detect the rainfall and close the lids.

To alleviate this problem, we have recently acquired two Boltwood cloud sensors. Currently, we open the lids at night whenever the dew point is below our threshold and it is not raining. To detect clouds, we simply take images of the sky and try to find stars automatically using SExtractor.[15] Once we install the cloud sensors, we will then be able to open the lids only when the sky is clear. Typically, one would like to open the lids or dome slits when the sun goes down in order to stabilize the temperature inside the enclosure and minimize the effects of dome seeing. However, for TAOS I the optical quality of the telescopes is not very good, so seeing does not affect the quality of our images. We can thus keep the lids closed and begin observing immediately when the sky clears without any degradation in performance. However, for TAOS II, we expect that the optical quality of the telescopes will be far better, and opening the dome slits at sunset will be desirable, even if it is cloudy. We plan to duplicate our weather monitor subsystem for TAOS II, so after installing the cloud sensors for TAOS I, we plan to investigate the possibility of predicting imminent rainfall using sky temperature data from the cloud sensor, dew point data from the humidity sensor, barometric pressure form the weather station, etc.

2.4 Control Software

The TAOS I control software is more complex than that of a typical small telescope system due to the fact that we needed to implement synchronous high-speed imaging with four telescopes. We got a significant head start on our software development by basing it on the ROTSE software package.[16] While we found the use of the ROTSE software invaluable, it used System V shared memory as a message passing mechanism, meaning that it would only work on a single machine. The TAOS I control system ended up comprising a network of twelve computers connected with a number of ad hoc inet sockets. Furthermore, the TAOS command set was significantly larger, and the shared memory message passing became unwieldy. For TAOS II, we have designed a new, lightweight and efficient message passing protocol as the first step in the software development process, and all remaining development will be based on this new protocol.

For TAOS I, we wrote a pipeline management system to replace the ad hoc set of sockets connecting the various software components running on different machines. This package was written in Python, and used a number of third party Python modules. After some time, we needed to upgrade our Linux OS (a very old version of Debian) in order to support newer replacement hardware. After upgrading the system, we found that all of the control software which was written in C (with the exception of the device drivers) compiled with no problems. However, the new version of Debian came with a new version of Python and new versions of the third party modules, and we found that Python had undergone significant changes, the APIs of the modules had completely changes, and the code no longer worked. After spending several months rewriting the pipeline management code, we found it suffered from significant memory leakage. After spending more time tracking down the memory leak, we concluded that the leak was in one of the third party modules, after which we gave up and returned to the raw socket connections. For TAOS II, we plan to make our control software as POSIX compliant as we can. This is not always possible (GUIs, device drivers, etc.), but we have found that is is most desirable to write a piece of code only once and not have to worry about it ever again. We have found Python and Perl very useful for data analysis and similar tasks where we are constantly trying to improve our techniques, but for the weather stations,

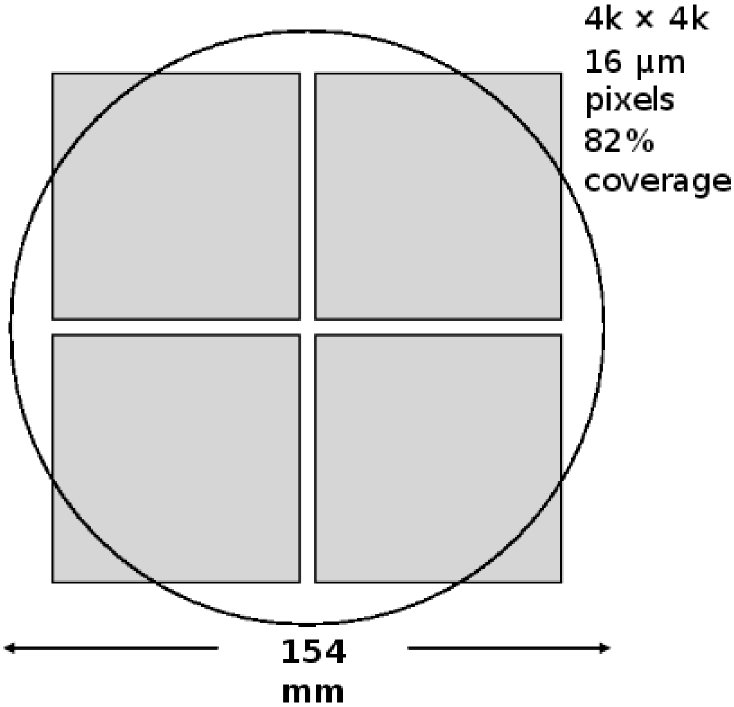

Figure 4. Left panel: USNO 1.3 m telescope, similar to the TAOS II model. Right panel: Possible layout of the TAOS II camera, using a mosaic of four 4k×4k CMOS images with 16 μm pixels.

for example, there is only one way to read the information from a serial port, and once we get it working, we do not want to rewrite the control software every time we upgrade the operating system. We will thus write as much of the control software as possible in C.

3. THE TAOS II PROJECT

TAOS II is a successor survey that will be more than one hundred times as powerful as TAOS I. The improvements will come from using better and larger telescopes (higher signal to noise), operating at a better site (more data), and using a camera with new CMOS imagers capable of reading out at a sampling cadence of 20 Hz (sensitivity to smaller objects).

TAOS II will comprise three telescopes manufactured by DFM Engineering (see Figure 4, left panel). The telescopes will be 1.3 m F/4 telescopes with a 3 □° field of view on a circle of diameter 154 mm. Contracts for all three telescopes have been signed, and they are scheduled to be delivered by early 2013.

The cameras need to be capable of high speed imaging on a large number of stars. TAOS II is planning on using the new monolithic CMOS devices manufactured by Sarnoff Inc. The new devices are back-illuminated, so 100% of the pixel area will be photon collecting. CMOS devices are also capable of sub-aperture readout. This will help keep the data rates to manageable levels. TAOS II will image 10,000 stars simultaneously with three telescopes at 20 Hz. Sub-aperture readout will reduce the data rate from 150 TB/night to about 3 TB/night. The new devices are thinned, and with an AR coating will have a quantum efficiency nearly as good as a CCD. Sarnoff has also reduced the read noise of the devices to 2 e^-. At this time we have not settled on the format of the imagers, but a possible layout of the camera is shown in the right panel of Figure 4.

TAOS II will be installed at San Pedro Martir Observatory (SPM) in Baja California, Mexico (see Figure 5). We are currently in the process of applying for permission to use the site, and we expect to begin site development in the autumn of 2011. All three telescopes will be installed by early 2013, and we expect to begin the survey in mid-2013. At this time, we will cease operations of the TAOS I project.

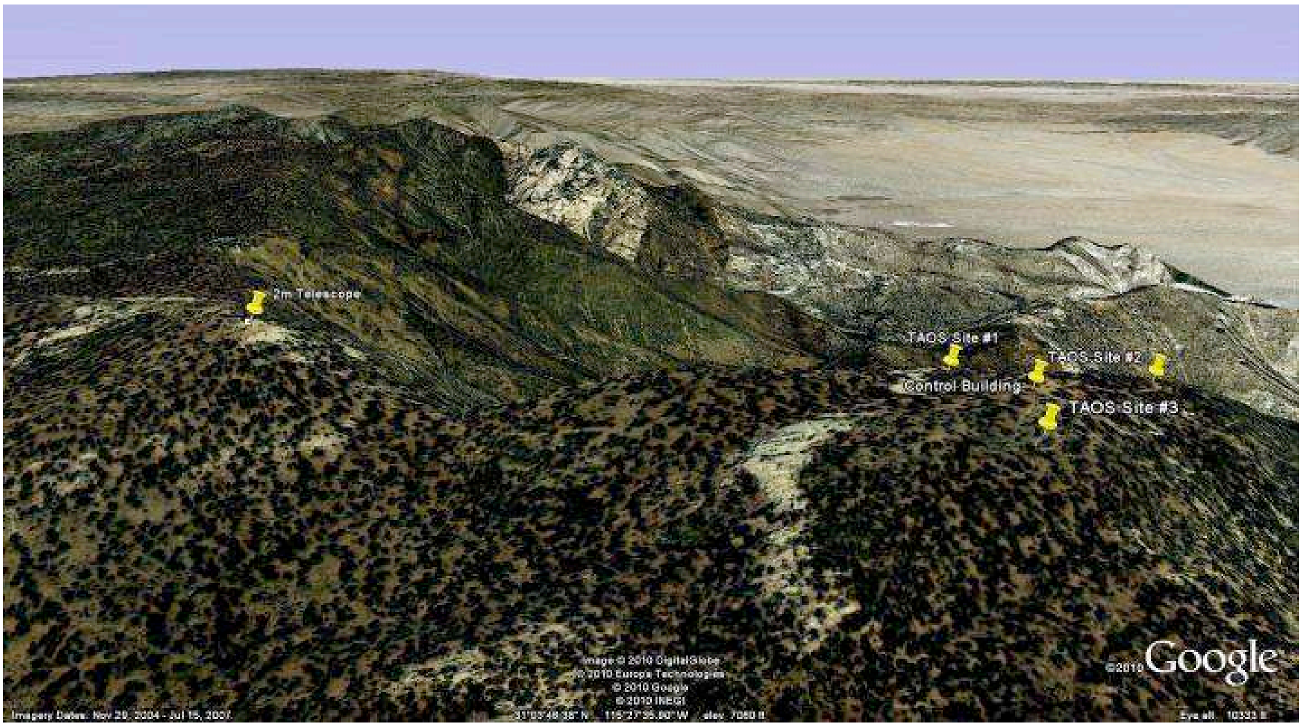

Figure 5. Image of the TAOS II site at SPM. The proposed sites of the three TAOS II telescopes and central control building are shown on the ridge to the right. The three telescopes are separated by distances of about 250 m. The location of the existing SPM 2.1 m telescope is shown on the ridge to the left.

4. LESSONS LEARNED

To summarize, we have learned the following lessons from our experience with TAOS I, which we will put to good use in the design of TAOS II:

- **Watchdog timer.** We found a watchdog timer system which will automatically close the dome in the event of software or computer failure to be invaluable. We are working with DFM Engineering to implement a watchdog system since they are manufacturing the TAOS II telescopes and will supply the dome controller.
- **Dome reliability.** Since SPM, the TAOS II site, does not suffer from the extreme wind conditions sometimes present in Taiwan, we are going to use a standard product for the dome rather than "reinvent the wheel." We will thus use domes from Ash Manufacturing.
- **Weather monitor subsystem.** We plan to duplicate the TAOS I weather monitor subsystem for TAOS II. We will use a set of three Vaisala weather stations, Vaisala humidity sensors, and Boltwood cloud sensors. We will use three sets of devices for redundancy and for detecting faulty readings. All devices will be recalibrated on the schedule recommended by the manufacturer.
- **Control software.** The control software will be built upon a design using a robust, lightweight message passing protocol. All code will be written in C wherever possible.
- **Technical staff on site.** The goal of both TAOS I and TAOS II is to implement a fully autonomous robotic observatory. However, in practice we found it fortunate to have staff on site in the event of the various hardware failures we encountered over the years. If staff had not been available to close the lids manually on several occasions, we would likely have had our telescopes and cameras severely damaged. The staff at SPM will be trained in manual emergency procedures for TAOS II.

ACKNOWLEDGMENTS

This work was supported in part by the thematic research program AS-88-TP-A02 at Academia Sinica. NKC's work was supported in part by the National Science Foundation under grant DMS-0636667. Work at the Harvard College Observatory was supported in part by the National Science Foundation under grant AST-0501681 and by NASA under grant NNG04G113G. The work at National Central University was supported by the grant NSC 96-2112-M-008-024-MY3. JAR's work was supported in part by the National Science Foundation under grant AST-00507254. SLM's work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and by Stanford Linear Accelerator Center under Contract DE-AC02-76SF00515. YIB acknowledges the support of National Research Foundation of Korea through Grant 2009-0075376. KHC's work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.

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