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Searching for NEOs using Lowell observatorys Discovery Channel Telescope (DCT)

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Abstract. We discuss the potential contribution of the Discovery Channel Telescope (or a clone) to a detection program aimed at discovering 90% of potentially hazardous objects (PHOs) larger than 140 m in diameter. Three options are described, each involving different levels of investment. We believe that LSST, Pan-STARRS, and DCT, working in a coordinated fashion, offer a cost-effective, low-risk way to accomplish the objectives of the extended NEO search program.

Keywords. survey; telescope; active optics; data management; data archiving; completeness

1. Introduction

Lowell Observatory's 4.2-m Discovery Channel Telescope is currently under construction at an outstanding new site in Northern Arizona (Fig.1). The product of a unique research and public education partnership between Lowell and Discovery Communications, Inc., the DCT offers uncommon versatility. Of particular relevance to NEO detection is the telescope's prime focus 2°-diameter wide-field imaging capability and its very rapid slew and settle time. In its alternative Ritchey-Chrétien, Nasmyth, and bent Cassegrain configurations, the DCT can bring an array of other instruments to bear on NEO characterization.

The 2360-m elevation Happy Jack site, on the Coconino National Forest 65 km SSE of Flagstaff, Arizona, was first identified following a years-long search, and was selected as the site for the DCT after an intensive site-testing program spanning all seasons. Median seeing, as measured in white light with a differential image motion system mounted a few meters above the ground, was found to be 0.84 arcsec, with the average of the best quartile seeing at 0.62 arcsec (Bida *et al.* 2004). The DCTs altitude axis will be about 12 m above the ground, so even better image quality can be expected. In November 2004, Lowell Observatory received a Special Use Permit from the U.S. Forest Service, allowing construction of the DCT.

The telescope, telescope enclosure, and the wide field camera designs were subjected to formal conceptual design review in July 2004. Since then, detailed design of the site infrastructure, telescope enclosure, and auxiliary building has been completed. The access road to the telescope site is finished, power and communications conduits have been brought to the site, and the buildings at the summit are well on the way to completion (see Fig. 2). The ULE meniscus primary mirror blank has been completed by Corning, and is undergoing figuring and polishing at the College of Optical Sciences at the University of Arizona. Meanwhile, designs of the telescope mount and wide-field corrector optics

Figure 1. Artists conception of the completed DCT installation.

have been further refined in response to issues identified during the conceptual design review. First light is scheduled for late 2009 or early 2010.

Figure 2. Aerial view of the DCT site, telescope enclosure, and auxiliary building (June 2006).

Telescope Facility. The DCT facility consists of a telescope building, auxiliary building, and equipment yard. The telescope building supports the dome, and includes the control room, computer room, instrument work room, and electrical equipment room. The heated work spaces below the telescope are insulated, and an intermediate airspace is flushed to prevent detrimental heat transfer to the observing chamber. The telescope mount is supported on an isolated foundation to avoid motion transfer from building wind loads. The auxiliary building is located away from the telescope building; it houses the mirror-coating facility and heat- and vibration-producing equipment, such as pumps and compressors. The equipment yard, next to the auxiliary building, includes glycol chillers, backup power generator, and propane, water, and sewage tanks.

Dome. The dome design is based on that of the similarly sized SOAR telescope dome. Using local wind statistics for computational fluid dynamics modeling of the telescope and enclosure, large ventilation openings around the equator of the dome have been included to minimize dome seeing effects. Incorporation of lessons learned from the SOAR dome is being considered in the detailed design of the DCT dome to improve its reliability and performance.

Mount. The telescope mount is a conventional altitude-over-azimuth design (Fig. 3), offering a $3°/s$ slew rate and a 6-s step and settle time for 2° offsets to adjacent fields. The design work is being performed by Vertex RSI, and draws on design experience with the SOAR 4.1-m and VISTA 4.0-m mounts by using similar or identical components for axial drives, bearings, and encoders. The mount structure is steel, with the exception of the tube truss elements, which are carbon composite to reduce thermal defocus sensitivity. Two top-end assemblies for the telescope will be available, enabling selection between the prime focus instrument and the secondary mirror for the Ritchey-Chrétien configuration. Finite-element analysis of the mount structure has been used to verify dynamic performance and deformations due to gravity and wind.

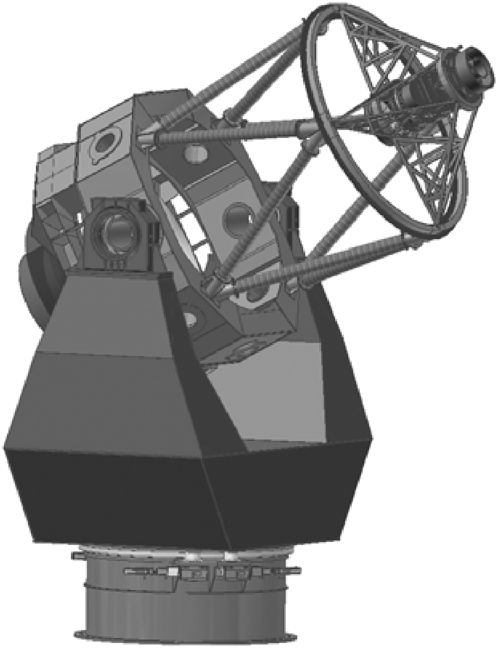

Figure 3. Rendering of the DCT mount in the prime focus configuration.

Active Optics. The active optics system provides active collimation and primary mirror figure control. In the prime focus configuration, collimation is achieved by a combination of actuation at the instrument support, and tip, tilt, and piston of the primary mirror using the figure control actuators. The primary mirror figure control system is based on the system developed for the SOAR telescope, with improvements to communications bandwidth necessary to support the step and settle requirements for the 2° offsets required by the NEO search mission. Optical and finite-element modeling has been performed to verify the correctability performance of the collimation and figure control systems.

Prime Focus Assembly. The DCT Prime Focus Assembly (PFA) consists of the Prime Focus Camera (PFC), the Wide Field Optical Corrector (WFOC), and the supporting spider structure. The PFC includes the CCD array, the dewar and cooling system, and the control and data-handling system to the point of initial data storage. Subsequent data handling, real-time analysis, archiving, etc., falls under the purview of the specific observational program for which the camera is used. The WFOC comprises the corrective optics, including an integral atmospheric dispersion compensator (ADC), filters and filter changer, shutter, and instrument rotator.

Key requirements for NEO search work have been factored into the PFAs design from the inception of the DCTs development. The requirements include image quality that degrades the median seeing by less than 10%; a single broad-band filter, encompassing the Johnson V and R passbands, for NEO and TNO searches; transmission from 330-110 nm; atmospheric dispersion compensation to a zenith distance of 75°; and CCD read time of 8 s or less, overlapped with a 6-s telescope move and settle for a 2° move.

The PFA has been the subject of several design studies carried out by EOST, Goodrich Corporation, and e2v. These companies delved into the optical design of the WFOC and its ADC (Blanco *et al.* 2002; MacFarlane and Dunham 2004, 2006), the mechanical aspects of the WFOC (Delp *et al.* 2004), and details of the PFC design (Dunham and Sebring 2004). Our current understanding of the PFA design derives from these studies, and is summarized here.

The DCT wide field optical corrector comprises five lenses (L1 through L5). L3 is an ellipsoid; L4 is the atmospheric dispersion compensator, which operates by means of a tilt and decenter mechanism; filters are placed between L4 and L5; and L5 is a 6th-order asphere. All elements are fused silica except for one Schott LLF6 or Ohara PBL6Y meniscus, the latter of which also provides the ADC function by means of a tilt and decenter mechanism.

The optical performance for a survey band broader than that envisaged for the NEO search is almost everywhere better than 0.5 arcsec FWHM, even at a zenith angle of 75°. Thus the design easily meets its image quality and ADC performance requirements.

The design has been scrubbed to improve the manufacturability and cost of the optics and to reduce their mounting tolerances. The opto-mechanical design described by Delp *et al.* (2004) has been simplified to take advantage of the change from a tumbling telescope top end to a swappable top end. A notable improvement in this regard is that the shutter is now commercially available through the University of Bonn. The design now rotates all components from the camera up to, but not including, the ADC element, which permits accurate flat fielding of frames. The ADC mechanism is a simple one-dimensional motion, with loose tolerances, using a flexure and cam to provide the necessary tilt and decenter motions. Focus and alignment of the PFA are accomplished by shimming and adjusting the primary mirror position and tilt through the active primary mirror support, as described above.

The PFC contains a CCD mosaic array mounted in a dewar and cooled to -100 C by four CryoTiger mechanical coolers. The last element of the WFOC serves as the dewar window. The focal plane is baselined as 40 e2v CCD44-82 CCDs. These are $2K \times 4k$ back-illuminated CCDs with 15 μm pixels and two output amplifiers. Thirty-six are used for science data, and 4 are set aside for guiding and wavefront curvature sensing, as shown in Fig. 4. The entire science array can be read out in 6 s, with read noise of about 6-8 e^{-}, using two NOAO Monsoon CCD controllers having synchronized clocks. A third controller will independently operate the guide and wavefront sensing CCDs. Focal plane data are delivered to the control and reduction computers in the computer room over a gigabit fiber network connection (Wiecha & Sebring 2004).

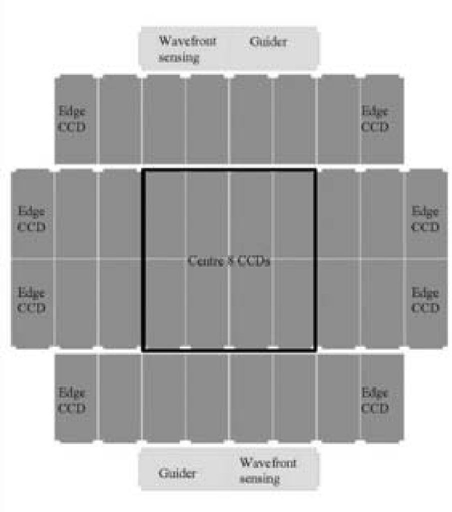

Figure 4. PFC focal plane layout. Pairs of CCDs at left and right are set aside for guiding and wavefront sensing.

We are taking advantage of lessons learned in similar large format cameras such as MMTs Megacam, VSTs OmegaCAM, CFHTs MegaCam, and the Kepler mission focal plane. The primary challenges in the PFC design are not related to the size of the array, per se, but to the fast focal ratio and the associated focal plane flatness requirement. A secondary issue is the basic logistical problem of cable routing. These items, the subject of the e2v study, were described by Dunham & Sebring (2004). The baseline approach is to use a lightweighted Invar mounting plate backed by a copper thermal spreader, all mounted using titanium flexures. This compromise, among gravitational sag, thermal distortion, and thermal conductivity, meets all our requirements. Cable management inside the dewar will be accomplished using custom flat flex cables and interface PC boards. The flex cables run from the science CCDs to interface boards located inside the dewar. The boards are not yet designed, but will include line filters and zener diode protection, and possibly preamplifiers as well. A second set of flex cables, potted into vacuum feedthroughs, will bring the signals outside the dewar. These cables will be terminated with more robust connectors to mate with the controller cables. Potting the cables into feedthroughs greatly reduces the required real estate on the dewar walls. This approach has been used in particle physics experiments and is in use with a Kepler test unit at Ball Aerospace.

2. NEO Detection Using the DCT

DCTs prime focus wide-field camera, with its 2.3 deg^2 FOV and 0.32 arcsec pixel size, will be a fine NEO search instrument. The tiling of the science CCDs on the sky plane has essentially no overlap and little area is lost to gaps between CCDs. The telescopes étendue of 39 m^2 deg^2 will exceed the total étendue of existing NEO search telescopes by almost an order of magnitude, which implies that DCT could, by itself, carry out NASA's current search for 90% of NEAs larger than 1 km in diameter in three or four years.

Our effort using DCT will concentrate on discovering and identifying potentially hazardous asteroids (PHAs: asteroids whose orbits pass within 0.05 AU of the Earths orbit), although other NEAs (aphelion distance q ¡ 1.3 AU) and comets, some of the latter also potentially hazardous, will be found in abundance. Note that, to a given diameter limit, there are about four times as many NEAs as PHAs. For PHA detection, using a *VR*-type filter (probably a long-pass Schott filter), the limiting magnitude of the camera/telescope system will depend on a number of factors, including the PHAs sky-plane motion and the chosen observing cadence. Nominally, we plan to make four exposures/night on a chosen region of the sky (two back-to-back 20-s exposures, repeated within, say, 30 minutes) and then to make similar observations on one or two additional nights during a lunation. Such a monthly cadence will provide the necessary self-followup, except for PHAs that "leak" out of the search region. In average seeing and moonless conditions, the cadence should lead to a limiting magnitude, for most PHA detected, of $VR_{lim} = 23.8$ (4.1σ above noise) on a single night. For PHAs detected on three nights, VR_{lim} should, on average, be near 24.1 mag.

Orbits for most PHAs observed on two or three nights/lunation will be accurate enough for meaningful Earth-impact calculations to be carried out by others within a few days to a few weeks of their discovery. Most PHAs larger than 140 m in diameter will be observed for more than one lunation, and the resulting ephemeris accuracy will be good enough, if necessary, for their recovery during a future apparition. Our observing cadence and planned rapid dissemination of moving-object astrometry will also facilitate expeditious physical observations by others. It is planned that all imaging data will be stored indefinitely, which will allow post facto searches to small S/N ratio.

To understand what DCTs 15-year search performance might be, we refer to Fig. 5 (from Harris & Bowell 2004), which pertains to a 10-year search to $V_{lim} = 24$ mag, a limiting magnitude close to what DCT will achieve.

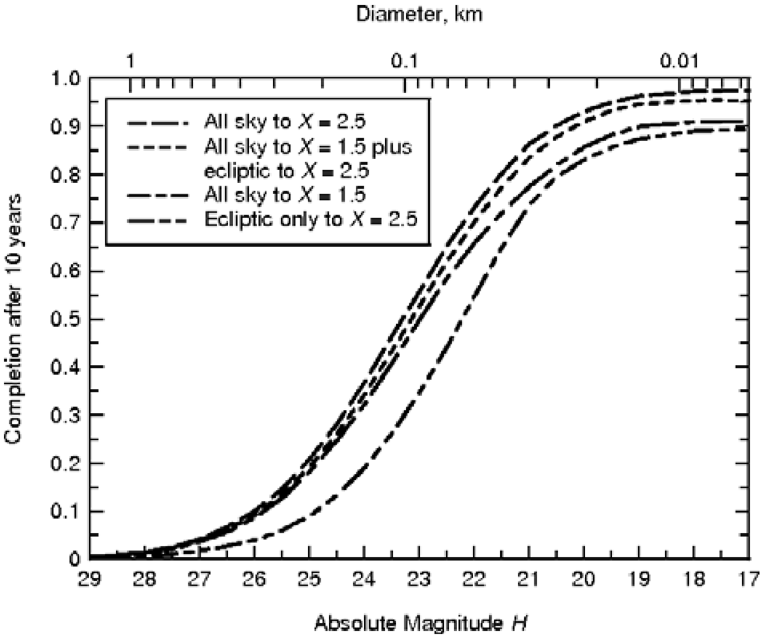

Figure 5. The estimated PHA completeness of various sky survey patterns as a function of PHA diameter/absolute magnitude.

The computations, using the method of Harris (1998), assumed that detections on two days out of three days observed in a month suffice for orbit determination. A moderate magnitude loss with air mass X of $dm_{lim} = -2.0logX$ was applied. Clearly, an all-sky survey is physically impossible, so the three upper curves represent upper bounds. Harris and Bowell showed that, for deep, wide-field survey telescopes such as DCT, it is profitable to confine PHA searches largely to an ecliptic-centered zone (although faint comets are more isotropically distributed).

Using the 3-nights/lunation cadence described above, DCT could, if dedicated 100% to PHA searching, observe an annualized average of about $4,000$ deg^2 of "fresh" sky/ lunation, which corresponds to an ecliptic zone about 17° wide covering the entire zodiac at solar elongations ¿ 60°. For a 2-night/lunation cadence, the areal coverage would increase by 50%. Thus DCTs predicted performance corresponds approximately to that of the lowest curve in Fig. 9, which represents a 20°-wide ecliptic zone covering solar elongations $> 45°$. Therefore, in a 10-year search, DCT could, by itself, discover about half of the PHAs larger than 140 m in diameter (for which, on average, $H \simeq 22.8$ mag). One can estimate the result of a longer search program by noting that the discovery rate of PHAs of a given size decays exponentially with time. Allowing for the lowest curves asymptote to 90% completeness for a search of infinite duration, we estimate that DCT could detect about two-thirds of PHAs larger than 140 m in diameter–about 15,000 PHAs–in 15 years.

We can estimate the number of PHAs of all sizes that DCT would detect in 15 years from Fig. 8 of Bowell & Muinonen (1994). Using an improved PHA population model, and ignoring trailing losses for very small, fast-moving objects, we find, very roughly, that DCT could detect about 10^6 PHAs, the median size of which would be just tens of meters. We estimate that, on average, about 40 PHAs per hour could be detected. In addition, we estimate that DCT could detect more than 5000 comets.

Slavish adherence to the ecliptic-zone observing regime is certainly not optimum for PHA detection. For example, after dusk and before dawn, it will likely be advantageous to observe in the so-called sweet spots (Stokes *et al.* 2003), on the ecliptic at small solar elongations, where the surface density of PHAs is enhanced. Note that DCTs atmospheric dispersion compensator provides good images to a zenith distance exceeding 75°. For 50% or 25% usage of DCT, the rate of PHA detection would, to first order, be cut proportionately, in which case the shape of the ecliptic-zone search region could be altered to reduce PHA "leakage". However, much more sophisticated numerical modeling than has hitherto been carried out is required to understand the effects of moonlight, interruptions due to weather and equipment failure, variable seeing, PHA rotational brightness modulation, and other impediments to optimum observing.

Finally, we note that DCT could usefully partner with other anticipated groundbased NEO search facilities. For example, LSST (southern hemisphere) and DCT plus Pan-STARRS (northern hemisphere) could, with careful coordination, observe the entire dark sky two or more times per lunation. Modeling the results of such a combined search effort has not yet been carried out, but one can be almost certain that NASAs mandate to catalog 90% of the impact risk within 15 years could be achieved using these three groundbased facilities alone.

3. Data Management and Archiving

The data processing and archiving stream will be based on the processing architecture of the currently operational Lowell Observatory Near-Earth-Object Search (LONEOS). A separate processor will be assigned to each CCD amplifier, just as at LONEOS, so an entire frame will be reduced in near real-time. With a planned exposure time of 20 s, a read time of 6 s, and a slew time of 6 s, the data rate will be 82 GB/hr and each processor will have 26 s to read and reduce a frame segment. LONEOS currently performs at approximately this rate using 2.4 GHz processors. The per-amplifier cost of computation will be similar to that at LONEOS. There we use dual-processor LINUX-based computers, one for each CCD.

We plan to use at least two reduction techniques. The first will be based on traditional source detection. Any NEO or PHA detected in this process will be immediately reported to the Minor Planet Center. The second technique, requiring far more computer processing, will be based on image subtraction, which is already in routine use at Lowell. All moving objects detected using these techniques will be made public as soon as possible, usually within a few hours of observation. Note that, although we have good methods linkage and orbit computation, they are not discussed here.

We plan to archive all frames. A typical night of 10 hours' observation will produce about 0.9 TB of data. Using the techniques developed at LONEOS, we will transfer the data to a RAID server and also keep a backup disks offline in a remote vault. We have developed software that can make these frames available to other researchers via the server. Higher density disks will become available as the project proceeds, so the number of archive computers will likely never exceed 20. Possibly, the archiving task could be outsourced.

To maintain data processing reliability, existing software will have to be slightly modified to permit continued data stream processing when one or more computers are unavailable. At LONEOS, the reductions are loosely synchronized to frame production, so if the reductions fall behind, the frames are statistically queued. By adding dynamic assignment of a reduction computer to a queue, the reduction stream will be able to tolerate multiple computer failures.

4. Schedule

As already noted, the construction of the DCT is well underway, and, if sufficient funds become available, will be completed by 2010. The PFA, which is not currently funded, will take about four years to construct. For a DCT clone, the time to first light is limited by the fabrication of the primary mirror, which it is thought would take about 4.5 yr. Thus "DCT2" could see first light by 2012 if funding is made available soon.

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† Most of these papers are available from `http:://www.lowell.edu/DCT/html/papers.html`