Abstract. The 0.91-m 'Spacewatch Telescope' of the Steward Observatory of the University of Arizona on Kitt Peak is dedicated to scanning with charge-coupled devices (CCDs) during the dark half of the month. We explored six modes of using CCDs for searches of gamma-ray bursters, debris in geosynchronous space, satellites of asteroids, brown dwarfs, the tenth planet, comets, cometesimals, and various types of asteroids. In the process, we gained experience with cosmic rays and artifacts in CCD observations. Each of these topics is described. I especially note that the existence of cometesimals has not been confirmed by the Spacewatch Telescope, contrary to reports published by others.

This paper describes a new discipline in astrophysics, 'scannerscopy', of surveying with a CCD rather than with photography at a Schmidt telescope. It uses the CCD in scanning rather than in sequencing of stare exposures as is done at most observatories. This may save telescope time, and flat-fielding is rarely needed. Usually we turn the drive off, but the scanning can be done with the telescope moving. In any case, the motion on the sky is precisely followed by slaving the charge transfer of the CCD to the drift rate of the image, while the CCD is read out continuously during the observing. Our primary application of CCD scanning is on moving objects such as comets and asteroids. We also do routine astronomy with CCDs, in a transit method, and this yields a precision of better than \( \pm 0.7 \) arc sec.

We presently use a Tektronix 2048 x 2048 CCD, 38 arc min wide, to a limiting magnitude of \( V = 20.5 \) (6\( \sigma \) detection). This is successful even for discovering rare and small near-Earth asteroids. 1990 UN with a diameter of 90 m and 1991 BA at 9 m are the smallest natural objects observed outside the Earth's atmosphere to date. In a month with good conditions we find typically 2000 new main-belt asteroids and, on average, nearly two near-Earth asteroids. Only the latter are followed up with astrometry. The goal is to study magnitude-frequency relations, as well as to complete the inventory of dangerous impactors on Earth. We are designing a new CCD-scanning telescope to become an order-of-magnitude more effective in the discovery of elusive objects than the Spacewatch Telescope. The paper also describes possibilities with cameras on spacecraft that pass through the asteroid belt; thousands of small asteroids can be observed with the CCDs of CRAF and CASSINI.

1. Introduction

The long-range goal for the CCD-scanning techniques that will be described in this paper is to survey the solar system to completion: to what limiting magnitude do we know the populations of various objects, particularly the faint ones such as comets, asteroids and satellites that can be distinguished by their apparent motion with respect to the stars? Are there any more outer planets or distant objects such as Chiron? How does the magnitude-frequency relation in the asteroid belt compare with those of comets, Trojans, and near-Earth asteroids? The latter are especially interesting in their origin and collisional history, their potential for space resources, and their hazards to our own survival.

I did some surveying of asteroids, Trojans, comets, and satellites with the Palomar 1.22-m Schmidt (van Houten et al., 1970, 1991; Gehrels, 1977). For a continuation with new equipment in Arizona the primary question was what techniques to use. I decided...
not to resort to the techniques of the 1930s, by using photography on Schmidt telescopes, but to aim at the techniques of the 1990s that might have large CCDs and affordable computers to handle the data stream. A comparison of the Schmidt and a CCD scannerscope was made in Gehrels (1984a). The next step was then to work with a simple CCD-scanning system in order to gain experience with various applications, while the extensive computer programming was being done for the eventual automatic detection and astrometry of comets and asteroids. There also was a financial reason to do various tasks, namely to keep the project funded in its early stages, when asteroid hazards and mining were not yet popular topics. In any case, we were having fun with new ideas, as will be shown in Sections 2–11.

For our own principal interest of observing comets and asteroids, the CCD has an advantage over photographic emulsion because it has a high quantum efficiency and wide wavelength range. On a long exposure with a Schmidt telescope an asteroid makes a trail, a spreading instead of integration; for the CCD the exposure time is shorter, and the asteroid is therefore detected more efficiently. Another advantage of the CCD is that the charge is accumulated linearly with integrated light flux — it fills a pixel well linearly until the well-capacity is reached — while photographic grain development changes nonlinearly for fainter objects. Thus, with the CCD the threshold for object detection is more sharply defined than it is for emulsions; if an object is discovered near the detection threshold it does not need to be observed so long. Another advantage of the CCD over emulsion is that it does not have reciprocity failure. A long exposure on a faint object gives the same result as short exposure on a proportionally bright object. Finally, the processing of CCD data can be made automatic and in real time with computer programming. This will be shown in this paper, especially in Section 13, to be a great asset when the programming is developed into a fine art.

There is a long history in astronomy of surveying with wide-angle cameras; historical precedent exists even for scanner-based systems. Indeed, the scanning that I will describe is similar to that done 90 years ago by George Ellery Hale with his original spectroheliograph, which matched the motion of the image plane to that of the photographic plate. The basis for CCD scanning is that the electronic signal charges can be transferred incrementally from one row of pixels to the next in a ‘bucket brigade’ process. Engineers use the term Time Delay Integration (TDI) for this, but we prefer the simpler word ‘scanning’. In any case, the rate of transfer is clocked to match precisely the rate at which the optical image of the star field moves across the CCD. This allows the CCD to be exposed and read out simultaneously and continuously for as long as the data collection system can store the accumulating scan.

Scanning can be done at rates from zero (a ‘stare’ observation) to about 24 rows per second for our 2048 CCD, and faster by more advanced devices. An example of using stares and scans for the same objects is in Section 6. For stare observations, time must be taken from the observing to read the frame into the computer. This may require half of the observing time! Of course, the CCD also has an integration time; the first ‘ramp frame’ has increasing integration for successive rows of pixels. If one needs the full field of the CCD, which occurs fully exposed on the frame after the ramp frame, and no