*Asteroids: New Observations, New Models*
*Proceedings IAU Symposium No. 318, 2015*
*S. R. Chesley, A. Morbidelli, R. Jedicke & D. Farnocchia, eds.*

doi:10.1017/S1743921315009187

# The Pan-STARRS search for Near Earth Objects

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**Abstract.** The two Pan-STARRS telescopes, located on Haleakala, Maui, Hawaii, are 1.8-meter diameter telescopes equipped with 1.4 Gigapixel cameras that deliver 7 square degree fields-of-view. The first of these telescopes, Pan-STARRS1, is conducting a search for Near Earth Objects, and is currently the leading discoverer of Near Earth Objects. The second telescope, Pan-STARRS2, is nearing the end of its commissioning, and is becoming more productive.

Pan-STARRS has become the leading survey for Near Earth Objects, responsible for approximately half of the NEO discoveries to date in 2015. Pan-STARRS is also the leading discoverer of new comets.

**Keywords.** surveys; minor planets, asteroids; comets; general

## 1. Introduction

The Pan-STARRS telescopes are wide-field survey telescopes, both located near the summit of Haleakala on the island of Maui, in Hawaii. At an altitude of approximately 3,000 meters, this is an excellent observing site. Although it is inferior to Mauna Kea on the island of Hawaii, both in terms of typical image quality, and weather, the median image quality is better than 1 arc second, and the site is one of the best observatory sites in the United States.

Each telescope has a 1.8-meter diameter primary mirror, a large secondary mirror, and a large camera mounted at the Cassegrain focus behind a corrector lens system. Each camera has almost 1.4 billion pixels, making them the largest digital cameras in the world at present. Each focal plane has 60 CCDs, arranged in an $8 \times 8$ grid, with the corners empty. Each CCD has $4800 \times 4800$ pixels, arranged in an $8 \times 8$ grid of cells that have $600 \times 600$ pixels. The CCDs were originally designed to use orthogonal transfer to move charge around to compensate for image and telescope movement, but this was not implemented due to cosmetic features in the CCDs that become larger when charge is moved around. The cell structure of each CCD means that fast moving asteroids have a relatively high chance of crossing an inactive cell boundary, and hence being corrupted. The cameras both have somewhat poor cosmetic qualities. The camera in Pan-STARRS1 has a 70% fill factor. The camera in Pan-STARRS2 is expected to have similar fill factor. Some systematic problems found in the Pan-STARRS1 camera have been corrected in the Pan-STARRS2 camera. The cameras have an approximately circular field-of-view, with a diameter of approximately 3 degrees. For the purposes of surveying, an inscribed hexagon is used to establish survey fields, with a small overlap at the edges.

Pan-STARRS was not originally designed with the intent of searching for Near Earth Objects. It performed a general purpose survey that included searching for Near Earth Objects, that started in 2010 and finished in March 2014. In April 2104, Pan-STARRS began to use 100% of its observing time searching for NEOs. Pan-STARRS presently spends 90% of its time dedicated to searching for NEOs, and that part of its operation is funded by the NASA Near Earth Object Observation program.

## 2. Survey properties

Pan-STARRS uses a broad "*w*"-band filter when the moon is below the horizon, or a relatively thin crescent. This filter is essentially the $r + g + i$ passbands combined and is has high transmission in the range 400–820nm. It has been optimized for dark conditions. The detectors in the Pan-STARRS cameras are extremely sensitive to light beyond 820 nm, and the filter eliminates the bright OH airglow beyond 820nm, which would produce a very high background if the telescope were to be used unfiltered. When there is a bright moon in the sky, the *i*-band filter is typically used; there are plans to construct a new broader infrared filter that will encompass $i + z$ to further increase sensitivity when the moon is up.

Pan-STARRS searches for moving objects by obtaining a sequence of four observations. These are pairwise subtracted to reveal moving objects. In most cases, the observations are spaced by approximately 20 minutes. When the sweet spots are being observed close to the Sun, observations are typically spaced by approximately 7 minutes, because of the limited time that the sweet spots are accessible.

The sequences of four observations are normally acquired in the form of "chunks" that take approximately 75 minutes to complete. Chunks span one hour of Right Ascension, and are cut into 7 declination bands between the celestial equator and the north celestial pole, and 6 declination bands between the equator and southern declination limit. Each chunk has 20–22 pointings to produce the typical 20 minute spacing between observations. Multiple tessellations of the observable sky have been created so that a deep image of the static sky can eventually be created, and used for subtraction.

Pan-STARRS reaches a depth of approximately $V = 22.5$ in dark conditions with the typical 45-second exposure time used to search for NEOs. The depth reached is dependent on the seeing — in poor seeing conditions the survey is less deep. And when the *i*-band filter is used in bright moon conditions, the limiting magnitude is approximately $V = 21.5$. Trailing losses for fast moving objects produce lower sensitivities for these objects.

The area surveyed spans from +90° in the north to −49° in the south. From the latitude of Pan-STARRS (+20°), the north celestial pole is at the same altitude as the extreme south fields that Pan-STARRS surveys; image quality in the south has proven to be surprisingly good. The deep southern sky has been very productive because most of the major asteroid surveys are located in the northern hemisphere; the southern sky has been somewhat neglected.

To date, with only one telescope, the area surveyed has been focused within 30 degrees of the ecliptic, and avoiding the Galactic plane during the dark moon period, and then moving away from the ecliptic (in the less sensitive *i*-band) during the bright moon period, partly by necessity to maintain an adequate moon avoidance angle which is required for wide-field telescopes.

Fields are typically repeated one night later (weather and moon permitting) to achieve some self-followup of NEO candidates. The discovery rate in good conditions can overwhelm worldwide followup resources. When both telescopes are in operation, the surveyed area will be expanded to higher ecliptic latitudes, and each field will be repeated more than once.

## 3. Overview of survey findings

The Pan-STARRS search for NEOs started by using pairs of observations. The original plan was to obtain three pairs of observations each lunation. This technique was not successful, because there were an overwhelming number of false detections that produced false tracklets. False detections came from inadequate background object subtraction, detector defects, cosmic rays, diffraction spikes (Pan-STARRS uses an altitude-azimuth mount, so diffraction spikes rotate and cannot be subtracted) and edge effects, and these combined to overwhelm the moving object processing system algorithms (see Denneau *et al.*, 2013). The detector fill factor, of approximately 70%, furthermore meant that the likelihood of obtaining three pairs during a lunation was $0.7^3$, or approximately 0.35.

In September 2010, the observations were changed to quads (a sequence of four observations), and NEOs were immediately discovered. The initial amount of observing time dedicated to the NEO search was only 5%, and this small fraction of dedicated observing time severely limited the discovery rate (see also Denneau *et al.*, 2013). The amount of time dedicated to finding NEOs was subsequently increased to 11%. At the same time, the general purpose survey was modified to acquire the $g$, $r$, and $i$ observations as quads, and this also led to an increase in NEO discovery. During this same time period, improvements in the image processing allowed fainter NEOs to be discovered, and the image quality achieved by the telescope was improved.

Each of these factors contributed to a slow improvement in NEO discovery rate from September 2010 until early 2014. Figure 1 shows the number of NEOs discovered by Pan-STARRS1 per month. The dramatic increase in early 2014 corresponds to when the telescope became a dedicated NEO search telescope. The major fluctuations in discoveries per month from 2014 onwards are directly related to the weather in Hawaii. The weather for astronomy in Hawaii was particularly poor in 2014 and in 2015 when a strong El Niño warmed the ocean around Hawaii.

Figure 2 shows a histogram of the H magnitude of the NEOs discovered by Pan-STARRS compared to the NEOs discovered by the Catalina Sky Survey. The distributions are markedly different. Pan-STARRS is deficient in discoveries of smaller NEOs. There are two contributing factors. The first is that some smaller NEOs that are seen by Pan-STARRS are not followed up, and therefore lost. Catalina obtains same night followup of fast moving NEOs, which makes recovery the next night more simple. In contrast, a fast-moving (small) NEO seen by Pan-STARRS may have a relatively large positional error 8 hours later when it is reported to the Minor Planet Center, and an even larger positional error 24 hours later when it is next observable from Hawaii. NEO followup resources west of Hawaii are sparse. We use the Canada-France-Hawaii Telescope (CFHT) to attempt to recover Pan-STARRS NEO candidates, but are not always successful.

The second reason that Pan-STARRS is deficient in smaller NEO discoveries is that fast-moving NEOs frequently trail over the (inactive) cell boundaries in the CCDs, and this corrupts their detection. As a result, only one or two of the detections may be clean. In order to report an NEO, we require three or four detections.

As a result, the archival Pan-STARRS data is rich in unreported NEO detections. We search archival data for a subset of recent discoveries, including PHAs and virtual impactors, but the present staffing level does not permit an exhaustive examination of archival data for missed NEO detections.

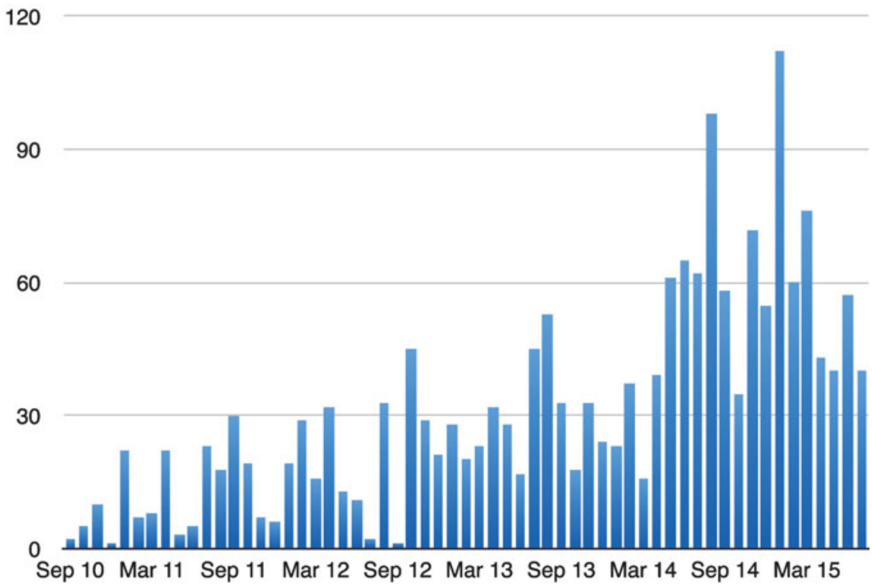


**Figure 1.** Number of NEOs discovered each month by Pan-STARRS1 since the survey began.

The 70% fill factor results in an efficiency of 70% in discovery of larger, NEOs that have slower motion. This has been empirically confirmed by repeating fields on a subsequent night, and discovering new NEOs that were missed on the first night. The discovery efficiency of Pan-STARRS could be improved to well over 90% by replacing the detectors in the focal plane with larger CCDs that do not have cell structure and good cosmetics. The ideal arrangement with commercially available CCDs uses 16 CCDs, arranged $4 \times 4$, each with $9000 \times 9000$ $10\mu$m pixels. The elimination of the cell structure would produce a dramatic increase in discovery efficiency for smaller, faster moving NEOs.

The depth to which the Pan-STARRS survey reaches has allowed it to continue to discover a significant number of large ($>$ 1 km) NEOs (9 in the period Jan–Sep 2015). If sustained, this rate will start to challenge the assertion by Mainzer *et al.* (2011) that 90% of these larger objects have been discovered, and will also test NEO models such as those by Bottke *et al.* (2002) and Granvik *et al.* (2015). Some of these large NEOs have large semi-major axis, and consequently a long period, which means we should expect to continue to discover similar objects for 5 or more years. Others have high inclinations, and spend much of their time well away from the more commonly surveyed ecliptic region.

Pan-STARRS has not yet discovered an NEO before impact, whereas the Catalina Sky Survey has discovered two (2008 TC3 and 2014 AA). In fact, Pan-STARRS may have seen impacting objects, but followup was not obtained. We have found that the MPC predicted positions for nearby NEOs may not be good; Pan-STARRS astrometry is typically good to 0.15 arc seconds, and curvature of the path of nearby objects is often evident. This curvature has been ignored in the MPC predicted positions. We have put into place new steps to recognize nearby objects, and expect to start discovering small impactors soon.

Pan-STARRS has relatively small pixels on the sky, and generally has good image quality. This combination has made it very sensitive to detecting cometary activity. In

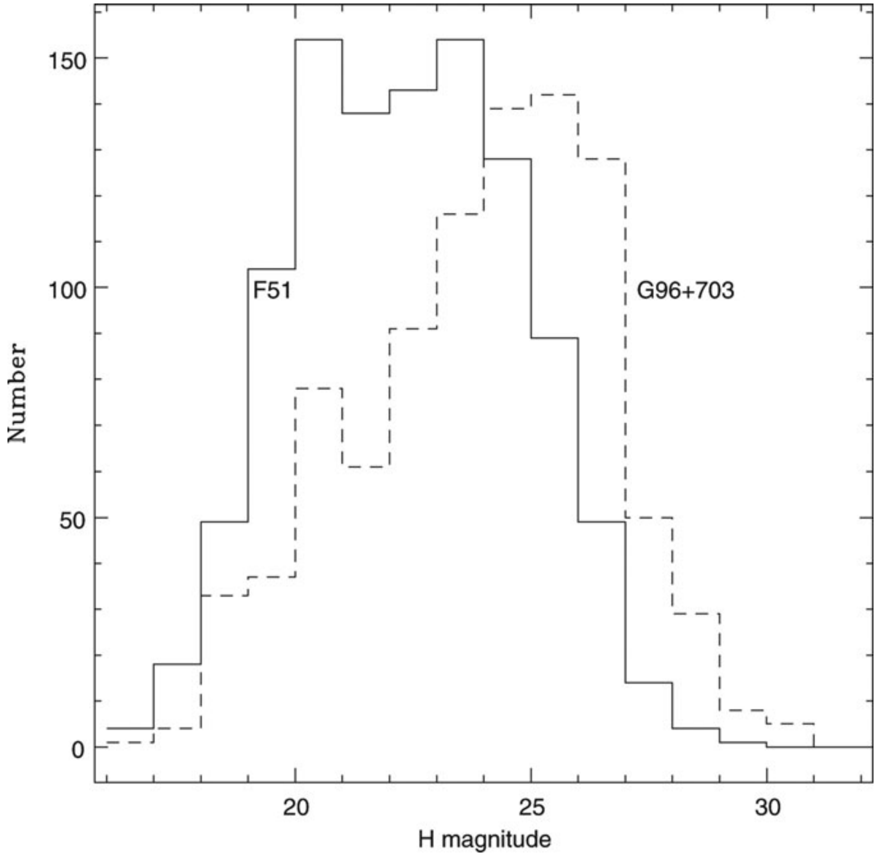


**Figure 2.** Histogram showing the distribution of H magnitudes for NEOs discovered by Pan-STARRS1 (F51) and by the Catalina Sky Survey (G96+703), during the period January 2014–July 2015.

2014, Pan-STARRS discovered more than half of the new comets, and has discovered more than half of the new comets to date in 2015. Pan-STARRS has also discovered several of the rare main-belt comets. Each night, all detections are screened for possible cometary activity, and likely comets are followed up using CFHT when it is available.

## 4. Summary

Over the last 5 years, the Pan-STARRS NEO survey has grown from a very modest beginning into the leading contemporary NEO survey. During the next year, as the second telescope becomes fully capable, the discovery rate will increase significantly, and the repeated field coverage should increase the discovery rate of smaller objects. The G96 telescope of the Catalina Sky Survey will soon have a new camera with a wider field. Together with the Pan-STARRS telescopes, a major improvement in survey capability will result. This will include improved orbits for many NEOs, and should start to correct the present situation where many NEOs are lost soon after they are discovered.

We expect that the Pan-STARRS survey for NEOs will continue well into the future.

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