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The Pan-STARRS Search for Near-Earth Objects

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Abstract. The Pan-STARRS telescopes, located on Haleakala, Maui, Hawaii, are conducting a long-term search of the night sky for Near-Earth Objects. The Pan-STARRS survey is now one of the leading NEO surveys, accounting for more than 40% of all new NEO discoveries, and over 50% of discoveries of larger NEOs. Pan-STARRS is also a prolific comet discovery telescope, and discovered the first interstellar object, ‘Oumuamua.

Keywords. Near-Earth Object, asteroid, comet, Earth impact hazard, survey

1. Introduction

Near-Earth Objects (NEOs) are defined as objects with perihelion less than 1.3 au. They can be asteroids or comets. The US congress instructed NASA to discover at least 90% of all NEOs with diameter > 1 km, a goal that is now believed to have been achieved Mainzer *et al.* (2011). This has since been extended to a goal of finding at least 90% of all NEOs with diameter greater than 140 m. In 2022, approximately 10,000 NEOs with diameter > 140 m had been discovered. This corresponds to approximately 40% of the expected number ($\sim$ 25,000) of these objects Harris and d’aBramo (2015). Contemporary surveys, including Pan-STARRS, are discovering these > 140 m sized asteroids at a rate of approximately 500 per year, or 2% of the population.

The Pan-STARRS telescopes are 1.8-meter wide-field telescopes located near the summit of Haleakala, on the island of Maui in Hawaii. Haleakala is the best site in the world for solar astronomy, and is also an excellent site for night time astronomy — arguably the second best site in the United States. For night time astronomy, Haleakala is inferior to Mauna Kea on the adjacent island of Hawaii. Haleakala is lower than Mauna Kea, which means that low-level moisture can more easily go over the summit. Haleakala has a large crater to the northeast of the summit that can produce turbulence with the prevailing northeast winds and make the seeing on Haleakala inferior to Mauna Kea. Maui is a smaller island with people living closer to the observatory and unfortunately has a weaker lighting ordinance than the island of Hawaii, resulting in a slightly brighter night sky.

Each telescope has a large (0.9 m) secondary mirror and a very large camera mounted at the Cassegrain focus. The Pan-STARRS1 (PS1) camera has almost 1.4 billion pixels, and the Pan-STARRS2 (PS2) camera has almost 1.5 billion pixels. These cameras are presently the largest digital cameras in the world, but will be surpassed by the camers on the Rubin Observatory when it becomes operational.

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The PS1 camera has 60 CCDs, and the PS2 camera has 64 CCDs. These are arranged in an 8×8 array, with the corners empty in the PS1 camera. The CCDs are Orthogonal Transfer Arrays (OTAs), each with an 8×8 grid of 600×600 active pixels and an inactive grid between the active cells. The intent of this design was to move charge around in the device to compensate for telescope shake to improve image quality. This functionality is not normally used, because it causes cosmetic defects in the devices to grow as the charge is moved around. The complexity of the fabrication of the OTAs resulted in devices that had more cosmetic defects than normal CCDs, and some areas of poor charge transfer efficiency that are unusable. The effective fill factor of each camera is a relatively poor 70%. The PS1 camera suffers from an image persistence problem when pixels have been saturated. The CCDs in the PS2 camera do not suffer from this problem. The OTA grid pattern is not ideal for discovery of moving objects because objects can move from the active cells into the inactive grid surrounding the cells.

Each camera has a field-of-view that is approximately 3 degrees in diameter, and 7 $\deg^2$ in area. Pixels in each camera are approximately 0.25 arc seconds. Typical seeing on Haleakala is approximately 1.0 arc seconds. Good seeing can be as good as 0.75 arc seconds, and usually coincides with light winds, of southerly winds. Both telescopes are operated remotely from the Institute for Astronomy office in Pukalani, Maui, which is approximately a 1-hour drive from the telescopes. Telescope operators can drive to the summit if there is an emergency need, but in practice, this is seldom necessary.

PS1 began operation in 2010 and spent its first 4 years doing a multi-purpose multi-color survey of the sky north of $-30°$ declination. The survey was completed in March 2014, and PS1 has been conducting a survey for Near-Earth Objects since April 2014.

PS2 was built in an enclosure to the north of PS1, and connected to the same building as PS1. PS2 has a stiffer telescope that points better than PS1. PS2 has optics that should eventually deliver image quality slightly superior to PS1. PS2 began surveying the sky for NEOs in 2018. Since 2021, it has had similar performance to PS1.

The Pan-STARRS search for Near-Earth Objects is funded by the National Aeronautics and Space Administration (NASA) Near-Earth Observations Program, which is part of the NASA Planetary Defense Coordination Office (PDCO). The vast majority of NEO discoveries at the present time come from programs sponsored by the United States via NASA and the PDCO.

The main aim of the Pan-STARRS survey is to find larger asteroids or comets that may impact Earth in the future, so that steps can be taken to deflect the object, eliminating the impact. Smaller asteroids that may impact Earth with only a few days warning may also be discovered. For these case, if the object is large enough that damage or injury is possible, warnings can be issued.

2. The Pan-STARRS NEO survey

Pan-STARRS presently searches for NEOs by obtaining a sequence of four 45 s exposures spaced over a time period of approximately 1 hour. These observations are usually obtained using a *w*-band filter, which has a bandpass of 400–820 nm. This filter is designed to maximize sensitivity, with wavelengths beyond 820 nm blocked to eliminate the bright OH emission in the near-infrared. The *w*-band filter is used when the moon is down, or up and less than 60% illuminated. When a brighter moon is in the sky, an *i*-band filter is used, and for the three nights closest to full moon, a *z*-band filter is used. Most of the NEO discoveries are made using the *w*-band filter because the sensitivity is approximately 1 magnitude deeper than with the *i*-band filter and bright moonlight. Because of the wide-field nature of the Pan-STARRS telescopes, a moon avoidance angle of 40° is generally used, so observations near full moon are typically taken away from the ecliptic.

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Observations are typically acquired in "chunks" which are groupings of approximately 20 adjacent pointings covering an area of approximately 120 deg^2. A chunk takes approximately 1 hour to complete. Chunks are 15 degrees wide (1 hour) in Right Ascension, with variable height in declination. As many as 10 chunks (or 1,200 deg^2) can be observed during a winter night with one telescope. The Galactic plane is generally avoided due to the high star density. Observations span the declination range $-50°$ to $+90°$. From the $+20°$ latitude of Maui, the north celestial pole is at the same elevation as $-50°$ declination. The Daniel K. Inouye Solar Telescope (DKIST) has been constructed to the southwest of Pan-STARRS, and its large enclosure obstructs parts of the southwest sky. This means that the southernmost declinations must be observed in the southeast as they rise or in the south. The southern obstruction of DKIST is less severe for PS2 since it is located north of PS1. In a typical lunation, most of the available sky can be surveyed at least once with each telescope, with some repeats possible in a lunation with good weather.

The images acquired by the cameras are transferred to computers at the University of Hawaii on the island of Oahu via a fast fiber optic-based network, where they are detrended, photometrically and astrometrically calibrated, and warped Magnier *et al.* (2020a), Magnier *et al.* (2020b). The primary technique presently being used to find moving objects uses pairwise image subtraction. Moving objects must be detected in a minimum of three of the four images. The moving object detection has a seeing-dependent lower limit of motion of approximately 0.05 deg/day, and an upper limit of 10 deg/day. Beyond 10 deg/day, there are too many false linkages producing for moving object candidates. Non-Gaussian noise from the CCDs produces many false detections. These false detections effectively limit the sensitivity of the survey; the number of false detections overwhelms the real detections if a faint detection limit is not imposed. As a result, some Near-Earth Objects go unreported by the moving object detection, but can later be manually measured and reported. Archival Pan-STARRS images are therefore rich in faint unreported asteroids, including unreported faint NEO detections.

A secondary NEO detection technique subtracts a deep stacked image from individual images, and searches for moving objects. A third technique is being developed which will use a static sky catalog and source detection in individual images. Each technique is hampered by noise and cosmetic defects in the detectors.

All moving objects have a "digest2" score calculated, which is a measure of how unusual the motion of the object is. Objects with digest2 scores greater than 50 are submitted to the Minor Planet Center (MPC), and rapidly processed. If they are not linked to a known object, or to an object already on the NEO Confirmation Page (NEOCP), they are posted to the NEOCP, and astronomers across the world attempt to obtain follow up observations, so that a preliminary orbit can be calculated.

NEOs usually, but not always, have unusual motion due to their proximity to Earth. NEOs can sometimes have motion that is typical of a main-belt asteroid, and those cases will have a low digest2 score and will not be posted to the NEOCP. NEOs that are headed directly towards Earth can also have very slow motion Wainscoat *et al.* (2022) that makes them difficult to recognize as moving objects. NEOs that are nearby may exhibit non-linear motion (curvature) across the sky due to the motion of the observer as the Earth rotates around its axis. The digest2 score does not consider curvature — instead it is based on the overall vector of motion of the object. At the present time, curvature must be recognized by an astronomer reviewing the moving objects, and the object forced onto the NEOCP.

All other moving objects are also submitted to the MPC, where they are either linked to known objects or stored in the Isolated Tracklet File. Moving objects are also screened for comets, which have a slightly extended appearance. Comet candidates are also reported to the MPC. Pan-STARRS presently discovers over 40% of all new comets.

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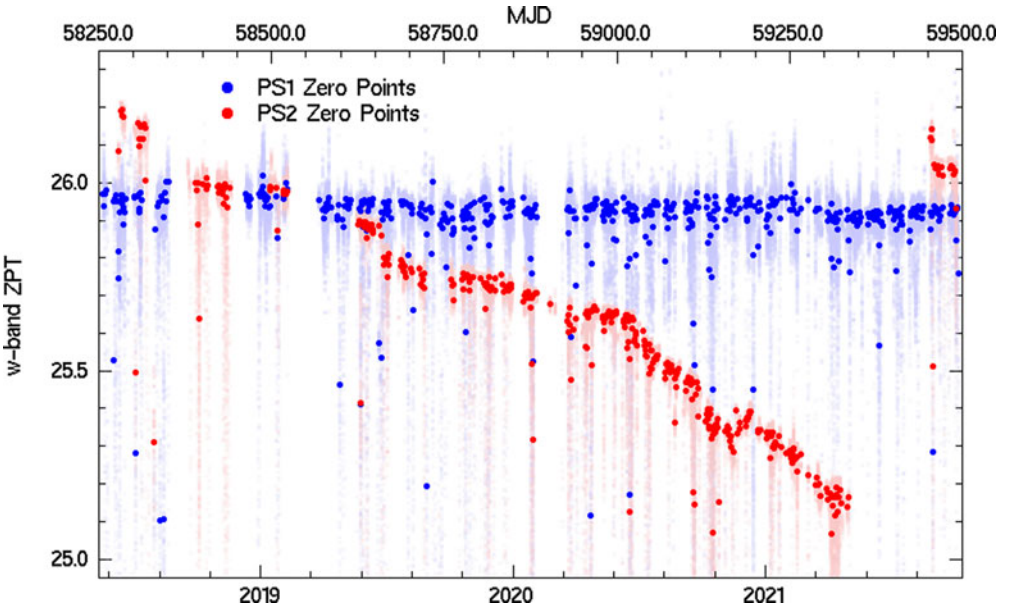


Figure 1. Photometric zero points for the Pan-STARRS1 and Pan-STARRS2 telescopes for 2018–2022.

3. Pan-STARRS2 secondary mirror problems

Despite optics that should have been better than PS1, PS2 lagged PS1 in NEO discoveries. This was initially attributed to poorer collimation and alignment, which was leading to poorer image quality. However, as the collimation and alignment was improved, the NEO discoveries by PS2 only increased modestly, and still lagged PS1.

Careful analysis of the zero points of the images showed that the throughput of PS2 was dropping quickly as shown in Figure 1. This was likely caused by the 2019 eruption of Kilauea on the island of Hawaii. The inversion layer kept the volcanic gases at lower altitude than Mauna Kea, but it is likely that some of these gases (notably sulfur dioxide) came to Haleakala where they produced serious degradation of the protected silver coating of the PS2 secondary mirror.

The PS2 mirror was removed for recoating and two excessively long screws were found to have been exerting pressure on the secondary mirror, producing astigmatism. This astigmatism was being partially removed by reshaping the surface of the primary mirror using actuators. Together, these non-ideal mirror shapes were contributing to poor image quality. Once the mirror was reinstalled, the astigmatism was gone from the secondary mirror and removed from the primary mirror, resulting in much improved image quality. The secondary mirror was coated with protected aluminum — the same coating used on the PS1 primary and secondary mirrors, and the PS2 primary mirror.

Now that the recoated secondary mirror has been reinstalled and collimated, discovery counts of NEOs from PS1 and PS2 are very similar, and the two telescopes have similar sensitivities.

4. NEO discovery statistics

The Pan-STARRS telescopes are the leading telescopes for discovery of larger (> 140 m diameter) NEOs, as shown in Figure 2. Pan-STARRS has a slightly larger aperture than the Catalina 1.5 meter telescope (observatory code G96) and better seeing conditions, making it able to see fainter NEO candidates.

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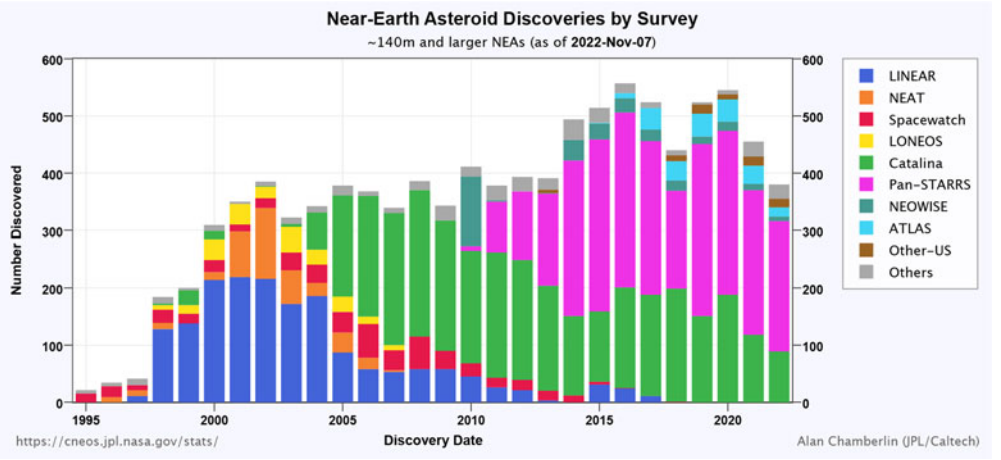


Figure 2. Discovery counts for 140-m diameter or larger NEOs. Pan-STARRS is colored magenta, and the Catalina Sky Survey is colored green.

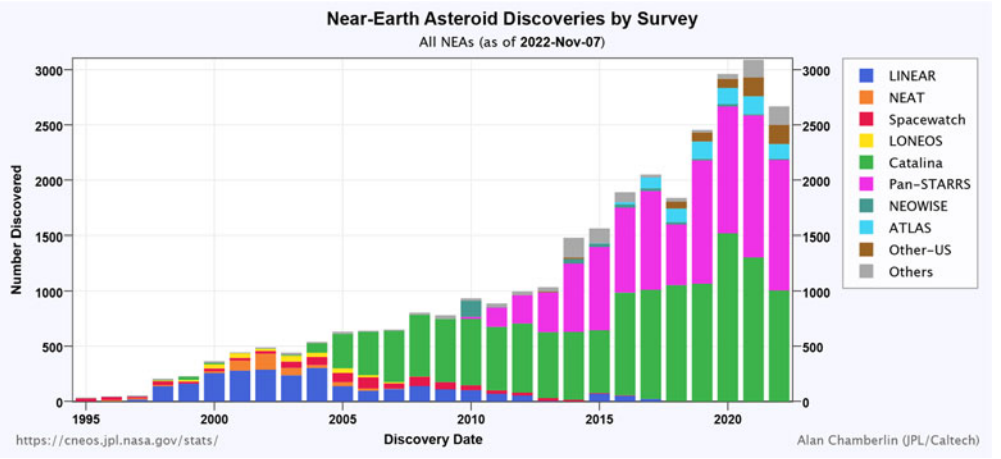


Figure 3. Discovery counts for all NEOs. Pan-STARRS is colored magenta, and the Catalina Sky Survey is colored green.

The Pan-STARRS telescopes are not as efficient at discovering smaller nearby NEOs and Atens because these faster moving objects often move into the cell gaps and their detections are corrupted. Figure 3 shows the discovery counts for all sizes of NEO, and shows that Pan-STARRS discovers a similar number of NEOs each year to the Catalina Sky Survey. Comparison of these two figures shows that the Catalina Sky Survey is more efficient at discovering smaller, faster moving NEOs.

4.1. *Reducing reporting latency and self-follow up*

For the period 2014–2020, most NEOs from Pan-STARRS were reported to the MPC on the morning following the observations. The basic rationale was that there were very few NEO follow up assets immediately to the west of Hawaii, so reporting NEOs in the morning HST was adequate for follow up from telescopes in Europe.

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Uncertainties grow quickly for rapidly moving NEO candidates — particularly for NEO candidates moving to the east. The lack of rapid follow up contributed to the inefficiency of Pan-STARRS in discovery of smaller, faster-moving NEOs.

Beginning in 2021, Pan-STARRS modified its reporting so that most NEO candidates are reported within a few hours of observations. This has been achieved by having astronomers in the Hawaii time zone report NEO candidates until approximately midnight HST, and an astronomer located in a time zone located well to the east of Hawaii report NEO candidates in the morning in that time zone.

The rapid reporting has in turn allowed Pan-STARRS to perform self-follow up of its own NEO candidates. This self-follow up, usually in the form of a pair of observations, extend the arc from 1 hour to approximately 3–4 hours. This is powerful because Earth's rotation provides parallax, which in turn constrains the distance of the NEO candidate, and constrains the positional uncertainty, making future recovery easier.

Self-follow up is not possible for NEO candidates discovered late in the night because the morning twilight interferes. The rising waning gibbous moon can also interfere with follow up.

5. Future prospects

It is clear that NEO discoveries by Pan-STARRS could be improved by replacing the cameras. The OTA CCDs are not ideal for NEO discovery, due to their cell structure, and the OTA CCDs also have cosmetic problems. Large format commercially produced CCDs are available, but are costly. Pan-STARS would need 18 CCDs of the size that Catalina and ATLAS use in their telescopes. The cost of the CCDs alone would be ∼$5 million for each camera

New cameras could double the NEO discovery rate by Pan-STARRS. The increase in discoveries would come from increased quantum efficiency, improved cosmetics, reduced noise, larger area covered. together with elimination of the cell structure. Maintaining the present 10 micron pixels is advisable. 9 micron pixels (as used by ATLAS and Catalina) are too small; 12 micron pixels would be acceptable. Teledyne e2V makes a suitable CCD with 10 micron pixels. These CCDs are slightly rectangular in shape. The focal plane could be covered using 18 of these CCDs, with a top and bottom row of 4 CCDs, and two rows of 5 CCDs in the middle.

New CCDs would allow longer exposure times to be used. Exposure times at present in the *w*-band filter are limited to 45 seconds, because of the image persistence problem in PS1. New CCDs would not suffer from this image persistence, and so could be used for longer exposure times. Longer exposure times would help discover fainter slow-moving NEOs. Extending the NEO search to fainter magnitudes would allow for synergy with the NEO discovery that is expected from the Rubin Observatory in the south.

5.1. *Interstellar Objects*

In 2017, Pan-STARRS1 discovered the first interstellar object, 'Oumuamua. 'Oumuamua was discovered on a night with poor seeing conditions. Many fast-moving NEO candidates that Pan-STARRS reports are not recovered, and it seems likely that Pan-STARRS has seen other interstellar objects in the past that were not recognized as being interstellar.

Now that two Pan-STARRS telescopes are operating nightly (weather permitting), the likelihood of additional interstellar object discoveries increases. The rapid self-follow up that is being obtained for most NEO candidates will extend observational arcs to approximately 4 hours, and provide insight into whether a fast-moving object is nearby or

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more distant, with its fast apparent motion caused by high velocity rather than proximity to Earth.

5.2. *Impacting Objects*

Although the Catalina Sky Survey and ATLAS have discovered a few very small asteroids immediately before impact, Pan-STARRS has not discovered an impacting asteroid. Pan-STARRS may well have seen a few very small asteroids before impact, but they were not recognized as impacting objects, and follow up observations were not acquired. Now that Pan-STARRS is acquiring rapid same-night self-follow up for most objects, it is likely that imminent small impactors will be more easily recognized, and adequate follow up acquired before impact. And now that two telescopes are surveying the sky nightly (weather permitting), the likelihood of Pan-STARRS discovering an imminent impactor is doubled. Discovering small impacting asteroids is of great interest, since their astrometric measurements produce real-world insight that will be useful for larger, more dangerous impacts. Photometry and spectroscopy can yield the size of the object before impact, and if the impact occurs over land, meteorite samples can be compared to the spectral measurements acquired before impact.

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