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2 The PanSTARRS PS1 NEO Survey

2.1 Introduction

The 1.8m diameter Pan-STARRS PS1 telescope currently operating on Haleakala, Maui, Hawaii, is detecting NEOs at a rate that will place it in the top 3 NEO discovery sites in 2011. Nearly 70% of the surveying is performed in modes that allow the efficient detection of moving objects, i.e. 4 or more images acquired at the same bore site within about a 100 minute time period. Figure 1 shows early results for less than the first quarter of the year. PS1 was in 3rd place in terms of NEO discoveries but we will present compelling evidence that the system has hit its stride and will perform even better in the remainder of 2011 and into the foreseeable future.

The PS1 system discovered a record number of 19 NEOs on the night of 30 January 2011 (UT) by dedicating the night to a survey mode designed to maximize NEO discovery. This is not the normal surveying mode but the nominal strategy is now about as good as it can be for NEO discovery given the constraints of other PS1 science goals. Figure 2 shows that the 19 NEOs in a single night from a single site is a significant accomplishment and that the only contemporary competition is from the two Catalina Sky Survey (CSS) sites.

This proposal requests funding to continue the PS1 NEO survey for 3 more years. The NASA funds will support PS1 Operations and the continued enhancement and operation of the PS1 Moving Object Processing System (MOPS). In the remainder of this proposal we will demonstrate that PS1 is currently discovering NEOs at a competitive rate and show that we will be able to continue and improve the performance during the time period covered by this proposal.

Figure 1 - PHAs and NEOs reported to the MPC in 2011 by the top 5 NEO discovery sites as of 10 March 2011.

Figure 2 - Maximum number of NEOs discovered at a single site in a single night for the 5 most prominent NEO survey programs. No other program discovered more than those shown in this figure. The month and year of the accomplishment for each program is given at the top of the program’s column.
2.2 Significance to the NEOO Program

As the largest aperture wide-field asteroid survey, and with its ability to rapidly image large areas of the sky even at low altitudes, PS1 is one of the best systems in the world to 'complete the inventory of the population of NEOs with diameters greater than or equal to 1 km' (NASA ROSES 2010 C.9 1.1). Its combination of faint limiting magnitude, superb location, and southerly latitude means that it can find the 1 km diameter asteroids when they are far from the Earth at opposition and when they are interior to the Earth's orbit in the 'sweet spots'. PS1 is more effective than other sites at discovering the objects down to 140 m in diameter because they are fainter.

A relevant by-product of the standard PS1 3pi surveying mode is that it automatically provides 2-color measurements of every detected NEO (not just the NEO discoveries) such that 1000s of NEOs will be color-characterized by the end of the grant period. PS1’s exquisite NEO astrometry and photometry will enable improved orbit determination and impact hazard assessment. The combined orbit, size and color information will enable an understanding of 'the characteristics of PHOs important for implementation of mitigation actions against a detected impact threat' (NASA ROSES 2010 C.9 1.2).

All the photometry and astrometry of all inner solar system asteroid detections will be provided to the MPC in a timely manner. PS1 has demonstrated the best astrometry of any existent or previous asteroid survey.

2.3 Technical approach & Methodology

2.3.1 The Pan-STARRS PS1 Telescope System & Performance

The Pan-STARRS PS1 telescope is located on Haleakala, Maui, Hawaii. It has a 1.8m diameter mirror and a 1.4 Giga-pixel CCD camera — the largest in the world — providing a 7 deg² field of view. The system regularly obtains 4 images per night of about 1,000 square degrees, reaches V~22 at 5-sigma in ~40 sec exposures, and detects moving objects with high efficiency (see section 2.3.2). There are 6 filters mounted on the telescope: g, r, i, z, y, and w. The g, r, i, and z filters are essentially the SDSS filters that allow a nice comparison to the Sloan Survey (e.g. Szabó et al., 2004) and the w filter is a wide bandpass filter optimized for asteroid detection that is essentially equivalent to g+r+i. The primary asteroid detection survey modes use the g, r, i, and w filters.

The PS1 Science Consortium (PS1SC, see section 2.3.7) operates the PS1 telescope and the PS1SC Director is Dr. Ken Chambers, IfA faculty member and co-I on this proposal. The PS1SC Director supervises the PS1 Observatory Manager, engineers and a team of 4 dedicated observers. About 60% of this proposal’s funding will go directly to PS1 Operations thru Chambers. At the time of writing the PS1 telescope has been operating well for about a year with a science observing efficiency of ~51% typical of contemporary mature telescope facilities. Table 1 provides a high-level

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1 The ‘sweet spots’ are regions of the sky near the ecliptic and between about 60˚ and 90˚ solar elongation. The sky-plane density of Potentially Hazardous Asteroids (PHA) is higher in this region than elsewhere on the sky for V>21.
breakdown of the fraction of time lost to weather and other problems during a night and the fraction of time spent in science observations.

Table 1 - PS1 Nightly Observing Statistics over roughly the first year of regular operations. Weather is the fraction of time that weather conditions are unsuitable for surveying. Downtime refers to mechanical or other problems when the telescope is not acquiring images but the sky is clear. Overhead is the time spent in activities that are a normal part of the survey but during which no science data is being acquired. E.g. telescope slewing, readout. Note that the overall science observing efficiency is about 51%.

<table>
<thead>
<tr>
<th>Night Activity</th>
<th>% of night</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>33%</td>
</tr>
<tr>
<td>Downtime</td>
<td>11%</td>
</tr>
<tr>
<td>Overhead</td>
<td>22%</td>
</tr>
<tr>
<td>Science</td>
<td>34%</td>
</tr>
</tbody>
</table>

Asteroids are detected in nearly 90% of the surveying time but about 63% of the surveying is in modes suitable for NEO discovery. i.e., multiple images acquired at the same footprint within a short period of time. About 56% of the observing is in the primary '3pi' mode in which 4 images ('quads') are obtained in 2 paired filters within a relatively short period of time on one night (e.g. 2 g-band images followed by 2 r-band images). Additional pairs and quads are obtained at the same bore sites up to 6x in one lunation. Since the typical time between the images is about 10-15 minutes we obtain color-characterization of each object (with the caveat that we can only properly correct for the light curve after we have sufficient observations; or we need to accept a systematic error in our color measurement due to not measuring the light curve). About 5% of the time is currently dedicated to targeted NEO discovery in the Solar System (SS) survey using the broad w-band filter (g+r+i). In this mode 4 images are acquired in a 30-60 minute period in fields near opposition as well as in the 'sweet spots' — regions near the ecliptic and with solar elongations in the range 60-90 degrees.
where the Potentially Hazardous Asteroid\(^2\) (PHA) detection rate is enhanced. Finally, about 25% of the observing time that is also suitable (but not efficient) for NEO discovery is in the Medium Deep (MD) survey mode in which 8 consecutive 240-second exposures are acquired at each location. We note that even though the MD fields are not well-placed for NEO discovery when an NEO is in the field they tend to be unusual objects.

Figure 3 graphically shows that the PS1 surveying area is comparable to that of the Catalina Sky Survey (CSS) but remember that the PS1 surveying covers many of the same fields multiple times in one lunation. Multiple visits to the same fields is necessary for the non-NEO PS1 science goals but is not detrimental to NEO discoveries because: 1) the PS1 camera fill factor of about 70% limits the asteroid detection efficiency in a quad to about 55% when we require either 3 or 4 detections. Thus, we have almost the same probability of discovering NEOs in the same fields on subsequent visits. 2) NEOs can move rapidly and enter the already-surveyed fields from surrounding regions. 3) NEOs change in brightness due to both light curve variations and by approaching the Earth and/or Sun and can then be discovered once they cross the limiting magnitude threshold.

The overall PS1 telescope system performance is shown in Figure 4 that illustrates the delivered FWHM realized on the image showing that we have a good handle on keeping the system delivering good quality detections. The Image Processing Pipeline (IPP) processes the images from the previous night by about noon the next day. Throughout the first year of operations the IPP provided source detections from ‘difference’ images obtained from same-filter images within quads (a different type of difference image is provided for the MD fields). In a g+r quad where the 1\(^{st}\) and 2\(^{nd}\) images are in g-band and the 3\(^{rd}\) and 4\(^{th}\) are in r band the IPP provided source detections in image\(_1\)-image\(_2\), image\(_2\)-image\(_1\), image\(_3\)-image\(_4\) and image\(_4\)-image\(_3\). Now that PS1 has been surveying for more than a year we have had the opportunity to build an image of most of the sky visible from Hawaii in each of the 6 filters (the ‘static-sky’) and the IPP will transition into providing detections by differencing each image with respect to the appropriate static-sky image.

\(^2\) PHAs are NEOs that can approach within 0.05 AU of the Earth’s orbit and have an absolute magnitude (H) brighter than 22.

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![Figure 4 - Cumulative FWHM distributions for 5 PS1 filters for the first year of PS1 operations. Note that the median FWHM in the 3 main solar system filters (g,r,i) is better than 1.3 arcsec.](image-url)
The IPP performs the astrometric and photometric measurements for each source detection. While there are some observers who report better astrometry to the MPC none of the other NEO surveys come anywhere close. Figure 5 shows that the PS1 astrometric residuals 'processed with debiasing for star catalog regional error (see Chesley, Baer & Monet, 2010) are about 0.15” and the other major surveys 'are significantly less accurate'. We do not yet have good statistics on the photometric uncertainty reported for asteroids in the PS1 data but at the most recent PS1SC meeting conservative limits were presented for stellar photometry of 5%, 2%, and 2% in the g, r, and i bands respectively. We expect that the uncertainty will be somewhat degraded for the moving asteroids but even if it is twice as bad it will still be far better than most observations reported to the MPC.

2.3.2 PS1 Moving Object Processing System (MOPS) & Performance

This section provides an overview of current MOPS operations. The MOPS development was managed for 6 years by the PI but in the past 2 years has been managed by Larry Denneau (co-I) who was and remains the lead MOPS software engineer. About 35% of the funding in this proposal is devoted to continued MOPS support and development.

IPP source detections from the difference images are provided to the MOPS that links detections of the same moving object in different images on the same night into 'tracklets'. Doing so required us to develop new algorithms to handle the Pan-STARRS data rate (e.g. Kubica et al., 2007). All real tracklets are typically provided to the MPC within about 24 hours and those with a high probability of being newly discovered NEOs are submitted as NEO candidates.

More than 95% of tracklets correspond to real objects but the fraction of tracklets that are real decreases as we increase the maximum allowed rate of motion. i.e. the fraction of tracklets with rates of motion typical of NEOs (higher than about 0.5 deg/day) is too large to allow the system to be automated. To compensate for this problem we have developed a ‘NEO Czaring’ website that allows human vetting of each NEO candidate tracklet and we have a small team of a half dozen scientists who act as ‘NEO Czars’. Figure 6 provides a snapshot of a portion of the Czaring website. It provides enough

![Figure 5 - Radial astrometric residual in arc seconds for PS1 detections and numbered asteroids reported to the MPC as of mid-May 2011. The median is ~0.15" with a slightly better mode. Figure courtesy of Andrea Milani.](image-url)
information for the Czar to decide whether the tracklet should be submitted to the MPC. The Czar has the option of submitting tracklets as NEO candidates, NEO follow-ups, or submitting incidental astrometry of large batches of asteroid detections.

Figure 6 – Five asteroid candidates that were submitted to the MPC from ‘quad’ tracklets obtained in the course of the 3pi survey. The NEO Czaring interface provides columns 1) a unique internal tracklet ID 2) the MPC ‘digest’ score that is related to the probability that the candidate is a NEO if the tracklet is real 3) the PS1 fields in which the tracklet was identified 4) the sky-plane speed of the tracklet 5) position angle of motion 6) great circle residual, i.e. the residuals between the tracklet’s detections and the best-fit great circle to the detections 7) the object corresponding to the detections (if known) 8) the object’s perihelion distance (if known) 9) submission status (either the PS1 identifier on MPC submission as shown here or a checkbox if the detections have not yet been submitted) and 10) ‘postage stamps’ centered on each of the detections in the tracklet. Note that we identify tracklets containing either 3 or 4 detections in the 3pi quads.

<table>
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<tr>
<th>Observatory Code</th>
<th>Observations</th>
<th>Numbered Minor Planets</th>
<th>Unnumbered Minor Planets</th>
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<th>Satellites</th>
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<tr>
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<td>77256</td>
<td>28449</td>
<td>21</td>
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<tr>
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<td>54405</td>
<td>2346</td>
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<td>2</td>
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<tr>
<td>CSS (703)</td>
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<td>60371</td>
<td>7420</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>Spacewatch (691)</td>
<td>263131</td>
<td>36668</td>
<td>8810</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>PS1 (F51)</td>
<td>161702</td>
<td>28852</td>
<td>11232</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2 - Total number of observations and corresponding number of objects of different types reported to the MPC in 2011 as of mid-May for the top 5 reporting surveys. The 6th survey reported less than half of the number of observations reported by PS1. The text of the proposal explains that PS1 has many more detections that will be reported even in this time period.

PS1+MOPS is in the competitive ranks for reporting asteroid detections to the MPC as shown in Table 2. While the top survey, CSS site G96, reported ~4.4x as many observations it reported ~2.7x as many observations of numbered minor planets and ~2.5x as many unnumbered minor planets. In other words, the CSS reports more observations per object than PS1 and is relatively less efficient at finding the faintest unnumbered and unknown asteroids. Being in 4th place may not be particularly memorable but it is important to point out that, due to reasons that will be solved well before the beginning of this proposal’s funding period, PS1 has only reported a small portion of its detections for 2011. We will report the full set of detections for 2010 and 2011 once the ‘Grand Reprocessing’ (see Section 2.3.8) is complete in the fall of 2011. Thus, by the end of the year we expect that PS1 will be in the 1st or 2nd position in terms of objects reported to the MPC.
The MOPS automatically links tracklets across nights within a lunation and fits orbits\(^3\) to these ‘derived objects’ as shown in Figure 7. The survey patterns are selected to overlap the same ‘chunks’ of the sky up to 6x/lunation and MOPS takes advantage of the overlapping by linking the tracklets together in an attempt to **identify NEOs that are ‘hiding in plain sight’** – objects whose rates of motion do not flag them as being interesting but whose orbits can identify them as such. This is a capability that no other NEO survey has implemented. We have yet to discover a NEO in this mode due to the fact that so few objects are imaged on \(\geq 4\) nights within a single lunation.

![Figure 7 - Eccentricity vs. semi-major axis for 1266 MOPS ‘derived objects’ in one lunation within the inner solar system. Derived objects are formed of detections obtained on at least 4 nights within the same lunation. The MOPS orbits for the objects clearly show the various sub-populations of Jupiter Trojans (near 5 AU), Hildas (near 4 AU) and the mean-motion resonances near 2.5 AU and 2.8 AU that divide the main belt into inner, middle and outer regions. Objects above the red line would be NEOs.](image)

Figure 8 - Main belt object detection efficiency as a function of apparent V magnitude in one of the evening sweet spot chunks. The solid line is a fit to the efficiency. The efficiency is measured by identifying known objects in the field and the V magnitude is the predicted magnitude of the object from it’s known absolute magnitude and distance from the Sun and Earth. Note that this represents the efficiency of identifying a detection of the object – not a tracklet. Thus, the plateau in the efficiency at just over 80% corresponds to the camera fill-factor. *i.e.* when an object falls on a live pixel it is detected by the IPP.

The PS1 system’s asteroid tracklet creation efficiency is about 55-65% for objects that are not saturated and not close to the system limiting magnitude. While this may seem low it is almost as high as it can possibly be given the camera fill factor of about 80% and that we require 3 or 4 detections in each quad’s tracklet (see Figure 8). The detection efficiency could be even worse since the Air Force Office of Scientific

\(^3\) The PanSTARRS MOPS system is fortunate in that we were granted permission to use JPL’s orbit determination and ephemeris generation software under the condition that we not distribute it further and do not use it for scientific research.
Research (AFOSR)\(^4\) removes large portions of the images that contain ‘streaks’. The streaks may be detections of satellites or image artifacts and their removal can affect 5-10% of images. Fortunately, since the MOPS team is based at the IfA in Hawaii, we have obtained special permission to use the difference image detections before the streak removal process.

### 2.3.2.1 The MOPS Cluster

![MOPS Cluster architecture](image)

Figure 9 - MOPS Cluster architecture. mops00-11 are all 2x2 Opteron nodes with 8 GB RAM. mops12 is a 4x4 Opteron system with 32 GB RAM. mops02 and mops03 each have 3 TB of disk space while each of the mops04-11 processing nodes have 500 GB of disk. LSD = low significance detections, a large but unsophisticated database of archived detections of S/N<5. mops12 runs known_server that attributes new tracklets to known objects.

The MOPS cluster as illustrated in Figure 9 is a mature system that has been running on synthetic and real data for more than six years. We have never lost data of any kind. All the hosts run 32-bit Gentoo Linux using the IPP system template for compatibility with the rest of PS1. All the hosts reside in a restricted network and are unreachable from outside the IfA. Two of the nodes (mops02 & mops03) are ‘master’-class nodes and have secondary network interfaces that make them accessible from the outside world as mopshq1 and mopshq2. For purely computational parallelized jobs we have a concurrency of about 32 on the processing nodes. Unlike most of the PS1 hardware, the entire MOPS cluster is located at the IfA in Honolulu.

For redundancy and reliability purposes the MOPS cluster uses RAID6 for data, and node-level (e.g. physical system) redundancy elsewhere. Furthermore, the operational MOPS databases are replicated continuously to the Pan-STARRS Published Science Product Subsystem (PSPS) – the final repository for all Pan-STARRS data. The PSPS is located on Maui and is therefore the MOPS off-site backup. The source code repository is also synchronized periodically off-site.

### 2.3.3 PS1 NEO Discovery Statistics (to May 2011)

As of the time of writing PS1 is the world’s 3rd most successful PHA and NEO discovery site as shown in Figure 1 and Table 3. It ranks higher in reporting high-probability NEO candidates to the MPC but these candidates are not converted into discoveries as effectively as achieved by the CSS because 1) PS1 does not provide self follow-up of its NEO candidates and 2) many PS1 candidates are too faint for follow-up by our follow-up collaborators (see section 2.3.6).

\(^4\) The primary Pan-STARRS funding agency.
The MOPS team has little influence over the self follow-up capability but we will explore the option of decreasing the exposure time in the w-band solar system survey to better match the follow-up sites’ capabilities (with concomitant increase in survey area).

To highlight the PS1 NEO discovery capability the MOPS team was given carte blanche on the PS1 telescope on the night of 30 January 2011 UT. We decided to use the w-band filter throughout the night and obtain quads of as many near-ecliptic fields as possible including regions in the evening and morning sweet spots and towards opposition. Everything worked nearly flawlessly that night. The IPP processed the images in a timely manner and we posted our first NEO candidate to the MPC at 9:16pm HST. We posted a total of 30 NEO candidates on the MPC NEO Confirmation Page that night and, with the dedicated help of a number of follow-up sites, 19 of those candidates were confirmed as NEOs as shown in Figure 2 — a new record for NEO discoveries by a single site in a single night. We are absolutely confident that at least 3 of the other 11 objects were NEOs based on their 100% digest score (essentially the probability that the object is a NEO). Those three objects were not followed up because they had high rates of motion and the weather at the standard follow-up sites was bad.

2.3.4 PS1 NEO Discovery Rate (during the period of this proposal)

Predicting the future discovery rate for the PS1 survey is difficult because it has only been operating in a regular and consistent survey mode since the beginning of 2011 – a time period during which weather and mechanical failures plagued the system.

We estimate our conservative NEO discovery rate as follows: In the first 4.5 months of 2011 PS1 discovered 64 NEOs in a survey mode where 5% of the time was dedicated to NEO surveying in the w filter and much of the remainder was suitable for asteroid detection but not necessarily NEO discovery. Since 19 of those 64 NEOs were discovered on NEO demo night (see Section 2.3.3) we discovered 45 NEOs in 4.5 months using a normal survey mode – 10 NEOs/month or 120 NEO discoveries/year. However, during most of the time period of this proposal we will have 10% of the time dedicated to NEO surveying using the w-filter. Since 30 of the 45 NEOs were found in the w-filter NEO survey mode we estimate that doubling the surveying time in the dedicated NEO mode would yield 75 NEOs in a 4.5 month period or 200 NEOs/year.
A more optimistic calculation uses the results of NEO demo night during which we had clear weather and a high recovery rate for high-probability NEOs. There were 19 NEOs discovered on NEO demo night plus another 2 objects that were clearly NEOs but were lost and a few other high probability NEOs. Assuming 20 NEO/night x10 nights per month (accounting for weather and other downtime as per Table 1) x 12 months/year = 2400 NEOs/year. With 10% of the observing time PS1 should discover 240 NEOs/year in the w-band survey alone plus 40 from the other surveying modes yielding a discovery rate of 280 NEOs/year. Allowing for a 50% increase in the NEO discovery rate in the other survey modes due to improved processing and follow-up increases the estimated discovery rate to **300 NEOs/year**.

An important consideration when evaluating the NEO discovery rate compared to other surveys as illustrated in Figure 10 is that **PS1 detects asteroids that are considerably larger than those discovered by other surveys**. Due to PS1’s larger aperture and fainter limiting magnitude **50% of the PS1 NEO discoveries are larger than about 240 meters in diameter** compared to about 120 meters diameter for the other surveys – nearly an order of magnitude in mass. Thus, PS1 has a much higher probability of detecting the more important PHAs than the other surveys.

### 2.3.5 Asteroid Color and Light Curve Characterization

PS1 is both a NEO discovery and characterization machine since it provides measures of their colors and light curves as described below.

One of the advantages of the **multi-band 3pi survey strategy** is that it provides **2-filter measurements** (*i.e.* one color) in a **short period of time for every observed asteroid**. Either g-r or r-i is measured on a single night and both are obtained for many asteroids in every lunation. We realize that these are not true color measurements

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5 Assuming an average albedo between S and C class asteroids.
because they are not coeval and there is no immediate method to correct for light curve effects. However, we think that this will simply introduce another error in quadrature into the color measurement and, considering that 1) PS1 photometry is much better than most other asteroid surveys and 2) light curve variations are typically small, we expect the PS1 colors to provide useful information about the NEO population – especially in identifying the most interesting objects with the strangest colors.

The utility of measuring colors for all asteroids including the NEOs is clear from the many interesting results from the Sloan Digital Sky Survey (SDSS, e.g. Szabó et al., 2004). Since the PS1 g, r, i, and z filters are essentially the same as the corresponding SDSS filters we will make direct comparisons between the asteroids observed in both surveys. The advantage to the SDSS colors is that they were all obtained within about a 5-minute time period and they were able to make a first-order correction for the light curve because the first and last bands were identical.

An advantage of the 4-visit solar system survey using the w-band filter combined with the good PS1 photometry is that it allows for the detection of objects with unusually large light curve amplitudes as shown in Figure 11. Objects with large light curve amplitudes may be binaries or contact binaries or simply objects with extreme shapes. The ability to rapidly identify specific unusual objects for detailed follow-up is important to characterize the NEO population. E.g. the frequency of contact binaries or objects with extreme shapes has implications for designing impact mitigation missions to ‘typical’ NEOs. Furthermore, the distribution of measured photometric differences within tracklets can be converted into a distribution of the triaxial ellipsoid axis ratios (a/b) for all asteroids using the techniques developed by Masiero et al. 2009.

**2.3.6 Follow-up Collaborations**

Since PS1 is not regularly capable of recovering its own NEO candidates we must rely on the follow-up capabilities of a group of dedicated observers located around the world. The vast majority of PS1 NEO follow-up has been orchestrated by the seven sites and collaborators listed in Table 4 - PS1 follow-up telescopes and collaborators. None of the follow-up sites receive any funding from this proposal. We recognize them here because of their important contributions in converting PS1 NEO candidates into PS1
discoveries. PS1 NEO candidate submissions to the MPC are automatically emailed directly to each of these sites and we recognize their contribution by explicitly including all of them as unfunded collaborators on this proposal.

One of the limiting factors in converting the large number of PS1 NEO candidates into NEO discoveries is that many of them are too faint to be recovered by most of the follow-up sites as illustrated in Figure 12. At the risk of appearing to contradict that statement, roughly half of all the PS1 NEO discoveries were fainter than $V \sim 21.5$ at the time that PS1 submitted them as candidates to the MPC – fainter than all other asteroid surveys are typically capable of detecting. This is possible because 1) NEOs sometime increase in brightness after they are identified by PS1 because of light curve or geometric effects and 2) some of our follow-up sites can reach fainter than $V \sim 21.5$ with effort and 3) one of our follow-up collaborators (Tholen) uses the UH 2.2m and CFHT 4m telescopes for follow-up and can easily reach $V \gg 22$ if he has available telescope time. Thus, we will consider decreasing our w-band.

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Code</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Hawaii 2.2m</td>
<td>568</td>
<td>D. Tholen$^6$</td>
</tr>
<tr>
<td>Las Cumbres Observatory, Faulkes Telescope North</td>
<td>F65</td>
<td>T. Lister</td>
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</tr>
<tr>
<td>Tenagra II</td>
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</table>

Table 4 - PS1 follow-up telescopes and collaborators. None of the follow-up sites receive any funding from this proposal. We recognize them here because of their important contributions in converting PS1 NEO candidates into PS1 discoveries.

Figure 12 – Fractional (solid) and cumulative (dashed) distribution of all asteroid detections (black) and NEOs (blue).

$^6$ Due to David Tholen being at the University of Hawaii and an important past and ongoing contributor to the PanSTARRS NEO effort he is the only contact/observer who is a co-l on this proposal rather than a collaborator.
exposure times to increase the rate of converting NEO candidates into NEO discoveries through better compatibility with the follow-up site capabilities.

2.3.7 PS1 Science Consortium (PS1SC)

The PS1SC operates the PS1 telescope with annual expenditures of about $3.5M. Their lease on the facility lasts until October 2012 with an option to extend the survey subject to funding availability and their interest in doing so. It is not yet clear what will happen once the PS1SC ceases to operate their all-sky surveys. It is possible that another consortium will be created to operate the system. It is also possible that the second Pan-STARRS telescope (PS2) will begin operations and merge its surveying capabilities with PS1 forming a much more powerful surveying system. Regardless of which entity operates the PS1 facility the IfA is committed to the NEO discovery mission and will ensure that the funding for this proposal is used to discover NEOs in the manner described here. If at any time we believe that the PS1 system will not be operated in a manner that will allow NEO discovery as described herein the funding should be terminated.

2.3.8 Continuing PS1 and MOPS Development

While PS1 is already operating well and finding NEOs competitively there are several improvements that will be implemented before the start of funding on this proposal.

A ‘Grand Reprocessing’ (GR) of all existent PS1 data back to the beginning of the survey will begin around mid-2011. The GR will implement a multitude of small and a few major improvements to the Image Processing Pipeline. Basically, all the improvements that have been implemented to the currently implemented pipeline will be re-applied to all the data so that the entire survey will have been processed consistently. The subsequent re-processing by MOPS will dramatically increase our statistics for reporting minor planet observations in 2010 and 2011 – perhaps elevating PS1 to one of the top 3 spots.

Another consequence of the GR and the survey having been underway for more than a year is that the full ‘static sky’ will soon be available for the differencing process as described briefly in Section 2.3.1. The static sky is the accumulated stacked image of the sky in each of the six PS1 filters. Newly acquired images will soon be compared (differenced) with the static sky allowing a deeper detection limit for the transient moving objects. At the end of the PS1 survey, when multiple images of each point on the sky are available over many years, another re-processing will occur using the multi-year accumulated static sky that will once again allow the detection and discovery of ever fainter asteroids. Thus, it is likely that PS1 will be the premier asteroid detection and discovery site from 2010 into the foreseeable future.

The MOPS is working very well but we will refine the operations to account for the implemented improvements in the IPP. We will also implement a trail-fitting algorithm into the IPP system. The IPP is very efficient at identifying nearly stationary detections in the images but once the motion becomes fast enough, perhaps 2 deg/day in the 3pi survey images, the detections become elongated and the detection efficiency decreases. But the IPP provides an interface to allow fitting of all source detections to any desired function and we will develop, test and implement a trail-fitting algorithm therein. Doing so will provide the speed and direction of motion of trailed detections
that is an important existing, but as-yet un-implemented, MOPS input to reduce the false detection rate at fast rates of speed. *E.g.* requiring that trailed detections in a tracklet have the same orientation and length. We expect that this technique will be implemented by late 2011 and certainly in early 2012.

The trail-fitting work described in the previous paragraph will have an added benefit in that it should dramatically reduce the rate of false source detections by producing a proper $\chi^2$ and flux value for trails (and also slow-moving objects because they are nothing more than short trails). *i.e.* requiring that the $\chi^2$ be reasonable will eliminate many of the false detections that lie on image ghosts, diffraction spikes or other artifacts. By reducing the false detections we reduce the false tracklets with our eventual intention being to automate the entire discovery and reporting process.

All the improvements described above will improve our discovery rate of new NEOs but probably not allow us to discover NEOs in the pre-existing data. We will certainly identify many new NEO candidates – but too much time has passed for these objects to be recovered and classified as PS1 discoveries. On the other hand, the large pool of NEO candidate astrometry and photometry from the reprocessed data will provide an excellent source for linking with past or new NEO observations. There will, of course, be a dramatic improvement in the reporting statistics for all asteroids, not just the NEOs.

### 2.4 Special Facilities

This proposal makes use of the PS1 telescope facility as described in Section 2.3.1. It will be provided by the UH and the PS1SC for this work. This proposal relies on the capabilities of the collaborators and co-I Tholen who provide follow-up measurements of the PS1 NEO candidates. The facilities are not funded by this proposal.

### 2.5 Impact on the field of Asteroid and Comet research

During the 3 years of funding provided by this proposal PS1 will be in continuous survey operations. We will report asteroid detections throughout the inner solar system to the Minor Planet Center on a daily basis. The number of minor planet observations will be comparable to that produced by the Catalina Sky Survey but the advantage of the PS1 data is 1) better astrometry 2) better photometry and 3) color information. The Minor Planet Center has told us that the PS1 observations have proven incredibly useful for improving asteroid orbits (Tim Spahr, personal communication). For instance, at a recent PS1SC annual meeting Spahr reported that the rate at which asteroids become numbered\(^7\) is now twice what it was previously due to PS1’s excellent astrometry.

Andrea Milani (collaborator) reports that the PS1 astrometric residuals are about 0.15" and the other major surveys ‘are significantly less accurate’. Furthermore, he states that ‘because of the superior quality of the PS1 data, effects previously negligible have a significant impact on the residuals. E.g., the PS1 data contain … a strong indication of regional biases in the 2MASS star catalog, at a level ≤0.1 arcsec.’ Thus, the PS1 data is uncovering errors in the standard astrometric error catalog that can be used to improve the astrometric reference system in advance of the Gaia preliminary catalog.

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\(^7\) ‘Numbered’ asteroids have the most accurate orbits.
2.6 General work plan

2.6.1 Milestones & Timeline

There are no specific milestones for this proposal. Regular PS1 operations are expected to continue with surveying in a mode that will produce ~300 NEO discoveries/year throughout the time period of the proposal. Throughout the time period we expect to make continual improvements to both PS1 operations and the MOPS.

The major issue in the timeline for this proposal is that at the time of writing the PS1SC is scheduled to cease existence in October 2012, only ~5 months after the start of this proposal. Discussions are currently taking place between the PS1SC and the Institute for Astronomy to explore options for continuing the PS1SC survey but at the time of writing it is impossible to predict what will happen. Regardless of whether the PS1SC continues to exist after October 2012 the PS1 will continue to be the property of the Institute for Astronomy and the IfA is committed to the NEO survey.

By the end of 2012 the PS2 system will be in commissioning mode and funding should be in place to operate that facility in a manner similar to that in which PS1 is currently operating. The PS2 system is essentially an improved version of PS1 – the latter being a prototype telescope. It is possible that PS1+PS2 could be coordinated in a improved sky survey as suggested in the proposal to the NEOO program this year by Kaiser.

In any event, should it transpire that the funding for this proposal ceases to be capable of generating NEO discoveries then the funding should be stopped.

2.6.2 Management Plan

Wainsoat (PI) was effectively co-PI on the predecessor grant to this proposal for the past two years. He will coordinate and be involved in all MOPS activities; manage the grant; be the direct supervisor of the IfA graduate student research assistant (Schunova), postdoc (Veres) and MOPS software engineer. He has been particularly involved in providing detailed survey strategy plans for the w-band solar system survey to the PS1SC every lunation.

Denneau (co-I) will manage the continuing development of the MOPS and direct the Pan-STARRS software engineer (Green) in implementing MOPS improvements and dealing with data processing issues. He will co-supervise the MOPS software engineer. Chambers (co-I) has the responsibility of running all PS1 operations for the PS1SC. He manages all the PS1SC PS1 employees including the four observers listed in this proposal as ‘Other Personnel’. He will ensure that the PS1 Ops funding described in the budget is disbursed properly.

2.7 Data sharing plan

All PS1 inner solar system asteroid detections (out to and including the Jupiter Trojans) for a night will be distributed the next day to the general scientific community through the MPC.

No non-public data or non-publically available software is shared with any of our foreign colleagues.
3 References


4 Biographical Sketches (alphabetical order)

4.1 Burgett (co-l)

Pan-STARRS Project Manager

Professional Preparation
University of California at Berkeley, Physics, A.B., 1977
University of Oklahoma, Physics, M.S., 1982
Johns Hopkins University, Physics, Ph.D., 1989

Appointments
Research Corp. University of Hawaii & Univ. of Hawaii Institute for Astronomy
Pan-STARRS Project Manager, Oct. 2005 – present,
University of Hawaii, Research Affiliate, 2004 – present
University of Texas at Dallas, Adjunct Prof. of Physics, 2004 – 2006
University of Texas at Dallas, Visiting/Clinical Prof. of Physics, 1999 – 2003
University of Texas at Dallas, part-time Lecturer in Physics, 1993 – 1998
Garcia Associates, contracted to TI/Raytheon, Senior Systems Engineer, 1994 – 1999

Recent Selected Publications
4.2 Chambers (co-I)

PS1 Director and IfA Faculty member

**Academic Degrees:**

- B.A., Physics, 1979, University of Colorado
- M.S., Physics, 1982, University of Colorado
- M.A., Physics and Astronomy, 1985, The Johns Hopkins University
- Ph.D., Physics and Astronomy, 1990, The Johns Hopkins University
- Post-Doctoral Fellow, 1990 - 1991, Leiden University, Leiden, The Netherlands

**Positions Held:**

- Director, PS1 System and PS1 Science Consortium, 2007–present
- Project Scientist, Pan-STARRS Telescope #1, Pan-STARRS Project, 2004–present
- Associate Astronomer and Associate Faculty Chair, Institute for Astronomy, 2002–present
- Adjunct Associate Professor, National Central University, Taiwan, Republic of China, 2007–present
- Associate Astronomer, Lick Observatory, University of California Santa Cruz, 2000–2001 (sabbatical)
- Associate Astronomer, Institute for Astronomy, University of Hawaii, 1998–2002
- Assistant Astronomer, Institute for Astronomy, University of Hawaii, 1991–1998
- Postdoctoral Fellow, Leiden University, The Netherlands, 1990–1991

**Honors:**

- Chretien Award, American Astronomical Society
- Regents’ Medal for Excellence in Teaching, University of Hawaii

**Publications - Closely Related To Proposed Project**

1. Kaiser, Nicholas; Aussel, Herve; Burke, Barry E.; Boesgaard, Hans; Chambers, Ken; Chun, Mark R.; Heasley, James N.; Hodapp, Klaus-Werner; Hunt, Bobby; Jedrzejko, Robert; Jewitt, D.; Kudritzki, Rolf; Luppino, Gerard A.; Maberry, Michael; Magnier, Eugene; Monet, David G.; Onaka, Peter M.; Pickles, Andrew J.; Rhoards, Pul Hin H.; Simon, Theodore; Szabay, Alexander; Szepudi, Istvan; Tholen, David J.; Tonry, John L.; Waterston, Mark; Wick, John, 2002, "Pan-STARRS: A Large Synoptic Survey Telescope Array". SPIE, 4836, 154

2. Hodapp, Klaus W.; Siegmund, Walter A.; Kaiser, Nicholas; Chambers, Kenneth C.; Laux, Uwe; Morgan, Jeff; Mannery, Ed, 2004, SPIE, 5486, 667

3. Barris, B. et al., 2004, “Twenty Three High Redshift Supernovae from the Institute for Astronomy Deep Survey, Doubling the Supernova Sample at z <= 0.7” Astrophysical Journal, 602, 571


**PUBLICATIONS - SIGNIFICANT**


**SYNERGISTIC ACTIVITIES**


**COLLABORATORS**


**GRADUATE ADVISOR AND POSTDOCTORAL SPONSOR**

1. S. M. Fall
2. G. K. Miley

**THESIS ADVISOR AND POSTDOCTORAL-SCHOLAR SPONSOR**

1. G. Knopp
2. B. Stalder
3. E. McGrath
4. P. Price
4.3 Denneau (co-l)
Pan-STARRS Senior Software Engineer and Pan-STARRS (MOPS) Manager

EDUCATION
Ph.D. (in progress), Astronomy, Queen's University Belfast, 2009-present
B.S.E.E., University of Arizona, 1990

WORK EXPERIENCE
Research Corporation for the University of Hawaii, Honolulu, HI
Pan-STARRS Senior Software Engineer Nov 2004 to present
Pan-STARRS (MOPS) Manager Jul 2009 to present

4D Technology Corporation, Tucson, AZ
Lead Software Engineer and Software Manager Sep 2004-Nov 2004

Pangalactic, Ltd., Tucson, AZ
Owner and Consultant 1998-2006

ArtToday, Inc., Tucson, AZ
Chief Technology Officer and Software Manager 1999-2002

Zedcor, Inc., Tucson, AZ
Lead Programmer 1996-1999

WYKO Corporation, Tucson, AZ
Software Engineer 1990-1993

PATENTS
USPTO #7079251, "Calibration and error correction in multi-channel imaging", inventors Brock, Neal J.; Denneau, Jr., Larry; Millerd, James E.; issued July 2006.

USPTO #5717782, "Method and apparatus for restoring digitized video pictures generated by an optical surface-height profiler", inventor Denneau, Jr., Larry; issued February 1998.

SELECTED PUBLICATIONS

Efficient intra- and inter-night linking of asteroid detections using kd-trees. Kubica, Jeremy; Denneau, Larry; Grav, Tommy; Heasley, James; Jedidke, Robert; Masiero, Joseph; Milani, Andrea; Moore, Andrew; Tholen, David; Waisncoat, Richard J. Icarus, 2007.
SUPERVISORY and MANAGEMENT EXPERIENCE
Research Corporation for the University of Hawaii
MOPS manager; Supervise D. Green.

4D Technology Corporation
Software manager; Supervised M. Schmucker

ArtToday, Inc.
Chief Technology Officer; Software department manager (5 engineers)

DESCRIPTION
I have been working as a senior software engineer for the University of Hawaii’s Pan-STARRS project since 2004. As the Pan-STARRS Moving Object Processing System (MOPS) lead engineer, I designed and implemented the software infrastructure that produces asteroid object catalogs from Pan-STARRS data. This work includes production of requirements documents, low- and high-level programming of astronomical algorithms from said requirements, systems integration between Pan-STARRS code and “industry-standard” code, large relational database development, inter-subsystem data transfer, end-user presentation, and testing. Much of the early MOPS development consisted of studies of large synthetic populations run through our pipeline to develop surveying and processing strategies and understand potential PS1 performance. In 2009 I assumed management of MOPS from Robert Jedicke, who resigned to focus more time on Pan-STARRS science. Recently I have contributed significantly to the Pan-STARRS 1 (PS1) telescope control subsystem, in particular the programming and execution of the PS1 survey. I regularly coordinate data transfer between Pan-STARRS and external organizations such as the Minor Planet Center, particularly in the area of NEO discovery. My overall continued enthusiasm for MOPS and astronomy has prompted me to pursue a remote Ph.D. in astronomy at Queen’s University of Belfast.

Prior to working at the University of Hawaii, I was lead engineer for 4D Technology Corporation, an interferometry and metrology company in Tucson, AZ. At 4D I managed and co-designed a complete end-user data acquisition and analysis application for characterization of optical surfaces for astronomy, aerospace and defense customers.

I have been involved in scientific programming since my undergraduate days at the University of Arizona, where I wrote data acquisition software for a geophysical firm, then accepted a position upon graduation at WYKO Corporation, the first of several metrology companies where I wrote software. During my years at these companies I enjoyed producing novel solutions to problems and was awarded several patents. In the mid-1990s I enjoyed a dot-com diversion at Zedcor, Inc., which later became ArtToday, Inc., where I developed commercial web applications and large (at the time) databases for non-scientific imagery.
4.4 Kaiser (co-I)
Pan-STARRS PI and IfA Faculty member

Academic Degrees
B.Sc. in physics 1978 Leeds University
Pt III Maths Tripos 1979 Cambridge University
Ph.D. in astronomy 1982 Cambridge University
thesis title: “Anisotropy of the Microwave Background Radiation”
supervisor: Prof. M.J. Rees

Current Position:
Astronomer at the Institute for Astronomy, University of Hawaii
Associate Director for National Telescope Projects
Principal Investigator, Pan-STARRS

Previous Appointments:
U.C. Berkeley Jan-Dec 83 Lindemann Fellow
U.C. Santa Barbara Jan-Jul 84 Post Doctoral Fellow
U.C. Berkeley Aug-Dec 84 Post Doctoral Fellow
U. Sussex Jan-Mar 85 SERC senior visitor
U. Cambridge May 85-Sep 86 Post Doctoral Fellow
U. Cambridge Oct 86-Apr 88 SERC Advanced Fellow
U. Toronto Apr 88-Mar 97 Professor at CITR

Honours:
Ontario Fellow of the CIAR Cosmology Program (1988)
NSERC Steacie Fellowship (1991-92)
Herzberg Medal of the Canadian Association of Physicists (1993)
Rutherford Medal of the Royal Society of Canada (1997)
Fellow of the Royal Society (2008)

Research Interests:
Observational Cosmology; Galaxy Formation; Large-Scale Structure;
Bulk Flows; Galaxy Clusters; Gravitational Lensing; Wide-Field Imaging
Near-Earth Asteroids

Relevant Publications:

### 4.5 Tholen (co-I)

**IfA Faculty member**

**Professional Preparation**

<table>
<thead>
<tr>
<th>Institution</th>
<th>Degree</th>
<th>Year</th>
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<tr>
<td>The University of Kansas</td>
<td>Physics B.S.</td>
<td>1978</td>
</tr>
<tr>
<td>The University of Kansas</td>
<td>Astronomy B.S.</td>
<td>1978</td>
</tr>
<tr>
<td>The University of Arizona</td>
<td>Planetary Sciences Ph.D.</td>
<td>1984</td>
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**Appointments**

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<tr>
<th>Year</th>
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<tr>
<td>1998-present</td>
<td>astronomer</td>
<td>Institute for Astronomy, University of Hawaii</td>
</tr>
<tr>
<td>1993</td>
<td>tenured at</td>
<td>University of Hawaii</td>
</tr>
<tr>
<td>1988-1998</td>
<td>associate astronomer</td>
<td>Institute for Astronomy</td>
</tr>
<tr>
<td>1983-1988</td>
<td>assistant astronomer</td>
<td>Institute for Astronomy, University of Hawaii</td>
</tr>
<tr>
<td>1982-1983</td>
<td>graduate research associate</td>
<td>Lunar and Planetary Laboratory, The University of Arizona</td>
</tr>
<tr>
<td>1978-1981</td>
<td>graduate research assistant</td>
<td>Lunar and Planetary Laboratory, The University of Arizona</td>
</tr>
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</table>

**Publications related to NEOs**


4.6 Wainscoat (PI)
IfA Faculty member & PS1SC Inner Solar System Key Project co-lead

Professional Preparation
University of Western Australia---Physics---B.Sc. with Honours, 1982
Australian National University---Astronomy---Doctor of Philosophy, 1987

Appointments
July 1999--present: Specialist (with tenure)
Institute for Astronomy, University of Hawaii
July 1998--June 1999: Specialist
Institute for Astronomy, University of Hawaii
January 1996--June 1998: Associate Specialist
Institute for Astronomy, University of Hawaii
July 1994--December 1995: Associate Astronomer
Institute for Astronomy, University of Hawaii
October 1989--June 1994: Assistant Astronomer
Institute for Astronomy, University of Hawaii
December 1986--September 1989: Postdoctoral Research Fellow
NASA Ames Research Center

Related Publications
Design of the Pan-STARRS telescopes: K.W. Hodapp et al. (including R. Wainscoat), Astronomische Nachrichten. 325, 636 (2004)
Management Experience

I have been a member of the Pan-STARRS and PS1 MOPS teams since their inceptions. During the past two years I have been co-PI with Dr. Robert Jedicke on a NASA NEOO program grant to support PS1 MOPS development, operations and NEO research. We worked closely together in supervising graduate students and postdocs, writing research papers, and interacting with Pan-STARRS and PS1 management on issues related to NEOs and asteroids. This experience places me in an ideal position to manage the functions required of me as this grant’s PI.
5 Current and Pending Support (alphabetical)

In accordance with the NRA instructions, work effort is provided for informational purposes only. The University does not intend to propose voluntary cost sharing by providing this information.

5.1 Chambers (co-I)
5.2 Denneau (co-I)

**Current Support:**

<table>
<thead>
<tr>
<th>Title of Award:</th>
<th>Panoramic Survey Telescope and Rapid Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>System (Pan-STARRS)</td>
<td></td>
</tr>
<tr>
<td>PI on Award:</td>
<td>Nicholas Kaiser</td>
</tr>
<tr>
<td>Sponsoring Agency:</td>
<td>Air Force Research Laboratory, Albuquerque, NM</td>
</tr>
<tr>
<td>AFRL Contracts Officer:</td>
<td>Ms. Liza Herrera, 505-846-6644</td>
</tr>
<tr>
<td>Performance Period:</td>
<td>04/01/11 – 03/31/11</td>
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<tr>
<td>Total Budget:</td>
<td>$0 (No Cost Extension from previous year in which award was $8,685,000)</td>
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<td>Commitment Per Year:</td>
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**Pending Support:**

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<tr>
<th>Title:</th>
<th>NEO Search and Characterization with the Pan-STARRS</th>
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<tbody>
<tr>
<td>PS1+2 System</td>
<td></td>
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<tr>
<td>Responsibility:</td>
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<tr>
<td>Award No.</td>
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<tr>
<td>Sponsor:</td>
<td>NASA Near Earth Object Observations</td>
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<td>NASA NEOO POC:</td>
<td>Lindley N. Johnson, 202-358-2314</td>
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<tr>
<td>Award:</td>
<td>TBD</td>
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<td>Performance Period:</td>
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## 5.3 Wainscoat (PI)

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<th>Title:</th>
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<tr>
<td>Sponsor:</td>
<td>NASA Near Earth Object Observations</td>
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<tr>
<td>Award:</td>
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<td>Award Date:</td>
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<th>Orbit and Number Distribution of Natural Earth Satellites</th>
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<tr>
<td>Award No.</td>
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<tr>
<td>Sponsor:</td>
<td>NASA Planetary Astronomy</td>
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<tr>
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<td>$297,000</td>
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<td>Award Date:</td>
<td>01/01/12 – 12/31/14</td>
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<td>Effort:</td>
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<table>
<thead>
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<th>Title:</th>
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<tr>
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</tr>
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<td>Sponsor:</td>
<td>NASA Near Earth Object Observations</td>
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<tr>
<td>Award:</td>
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<tr>
<td>Award Date:</td>
<td>01/01/12 – 12/31/14</td>
</tr>
<tr>
<td>Effort:</td>
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6 Budget

6.1 Personnel and Work Effort (in alphabetical order)

<table>
<thead>
<tr>
<th>Personnel</th>
<th>% contribution to this proposal</th>
<th>% of total effort during grant period</th>
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<tbody>
<tr>
<td>Ken Chambers (co-I)</td>
<td>20%</td>
<td>90%</td>
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<tr>
<td>Larry Denneau (co-I)</td>
<td>10%</td>
<td>20%</td>
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<tr>
<td>Andrea Milani (collaborator)</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td>Eva Schunova (grad)</td>
<td>10%</td>
<td>50%</td>
</tr>
<tr>
<td>Peter Veres (post-doc)</td>
<td>20%</td>
<td>100%</td>
</tr>
<tr>
<td>Richard Wainscoat (PI)</td>
<td>20%</td>
<td>25%</td>
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</table>

Table 5 – Percentage contributions of personnel to the proposed research.

Note that the list of personnel in Table 1 is curtailed relative to the full list of co-Is, collaborators, etc. The 2011 NASA Guidebook for Proposers states that this table should list those people ‘required to perform the proposed investigation … regardless of whether those individuals require funding’. While PS1 does require follow-up from our listed collaborators no one individual collaborator is ‘required’. Similarly, while the other listed co-Is who are not indicated above will provide valuable and regular input to the proposed investigation they will not be specifically contributing a significant proportion of their time to this work.

Furthermore, PS1 is a large ongoing survey project with many employees including a telescope manager, IPP software engineers, and four observers. These people are clearly necessary for the proposed investigation but only the observers will be partly funded by this successful proposal. Rather than calling them out individually we have included their contribution under Ken Chambers (co-I) who will supervise them in his role as PS1SC Director.

The MOPS personnel are called out individually because they have specific and different roles within the MOPS component of this proposal.

6.1.1 Chambers (co-I)

Ken Chambers spends virtually all of his time as the PS1 Director as shown in Table 1. It could be argued that all that time is necessary for this proposal but he will specifically manage and ensure the timely delivery of the components that are called out in this proposed investigation: the PS1 utilities, Maui High Performance Computing Center (MHPCC), vehicle leases and server maintenance. He will continue to supervise, train and hire four PS1 telescope observers as necessary.

6.1.2 Denneau (co-I)
Denneau will continue to be the MOPS Manager and Senior Software Engineer. While the MOPS software is essentially mature, and long ago met all its requirements, there is a need for continued MOPS support and improvement as the PS1 system improves. In particular, as the IPP has evolved the data provided to the MOPS has changed and this requires modification to the interface between the systems. During the time period of this proposal we will hire a junior software engineer to work on MOPS under Denneau's direct supervision.

6.1.3 Milani (collaborator)
Milani has been working with the Pan-STARRS MOPS team for most of the last eight years. He has provided critical analysis and orbit determination software to MOPS and regularly provides updates to improve their operation within MOPS. Each summer for the past six years Milani has visited the IfA for a month to provide hands-on assistance with MOPS development and, more recently, MOPS system quality control. E.g. measuring the system’s efficiency, astrometric and photometric accuracy. Milani will continue to provide these services to MOPS and the PS1SC during the period of this grant.

6.1.4 Schunova (graduate student)
Schunova will perform NEO Czaring, assist in assessing the performance of the MOPS system, and perform NEO research.

6.1.5 Veres (post-doc)
Veres will perform NEO Czaring, have the primary responsibility for assessing and monitoring the performance of the MOPS system, and perform NEO research. He will be the primary interface between the MOPS software team and the scientific assessment of MOPS data products.

6.1.6 Wainscoat (PI)
Wainscoat will co-manage with the PI all the grant proposal functions, including the hiring and supervising of the post-doc (Veres) and graduate student (Schunova) and hiring the junior MOPS software engineer, be involved in all research efforts, perform NEO Czaring, and assist in writing and editing each of the papers.
6.2 Facilities and Equipment

The University of Hawaii at Manoa and Institute for Astronomy supports the use of its facilities for this program. All facility use is contingent upon availability however every effort will be made to accommodate this program. Facility access does not constitute a commitment of voluntary cost sharing.

This proposal relies only on existing facilities and equipment at each member’s institution.

The primary and only absolutely necessary facility for this proposal is, of course, the PS1 telescope on Haleakala, Maui, Hawaii. All the co-Is are intimately involved with the development, operations and capabilities of the PS1 system.

All the non-critical follow-up sites maintain their own observatories.

The PI and all but one of the co-Is are faculty members at the University of Hawaii’s (UH) Institute for Astronomy (IfA), one of the world’s leading astronomical research centers. All UH faculty have enhanced access to all the astronomical facilities on Mauna Kea. Briefly, all the observatories at Mauna Kea must provide on the order of 10% of their observing time to UH astronomers. Some telescopes, such as the 2.2m facility, are wholly owned and operated by the UH and most of its time is available to UH members. Faculty must still compete through internal Telescope Allocation Committees (TAC) for telescope time but the likelihood of being granted observing time is higher than for researchers applying from outside the UH system.

In particular, the IfA faculty members have enhanced access to all the premier telescope facilities on Mauna Kea including Keck, Gemini, SUBARU and also CFHT, IRTF, UKIRT and the UH 2.2m. All these telescopes have imaging cameras and spectrographs that we could use for NEO follow-up covering the wavelength range from the visible to infrared. The CFHT is particularly useful for NEO recovery in its queue-mode observing program with the Megacam wide field camera (1 deg²). The UH 2.2m is also well matched to PS1 NEO candidate follow-up and will be useful for physical characterization through color-photometry and spectroscopy with its integral field unit (SNIFS). Indeed, PI Wainscoat and co-I Tholen already regularly obtain time on both these telescopes for PS1 NEO follow-up.
6.3 Budget Details

6.3.1 Introduction

Roughly 60% of this proposal’s funding will be provided directly to the PS1 operations team lead by co-I Chambers. The roughly $600K/year for PS1 operations corresponds to ~17% of the PS1 system’s annual operating cost but the PS1SC surveys in a NEO-discovery mode about 65% of the time. To provide simple and specific line items in this budget we will specifically direct the NEOO funding to only 5 sub-categories of PS1 operations: PS1 observer salaries, utilities, computer center fees, vehicle leasing and server maintenance.

The remaining 40% of the funding will be directed to supporting the MOPS team operations lead by the PI Wainscoat. Most of these funds are directed to salary for the junior members on the team.

None of the senior personnel on this proposal are requesting salary support. Full salary support is requested for a MOPS graduate student research assistant (Schunova), a MOPS post-doc (Veres), and a MOPS junior software engineer (TBD). Partial support is requested for the team of 4 PS1 observers.

We request travel support to enable the senior personnel, graduate student and post-doc to attend and present their work based on this proposal at national and international conferences.

If this proposal is accepted the award instrument should be a grant to the University of Hawaii.

6.3.2 Preamble

6.3.2.1 Department of Health and Human Services

The cognizant administrative contracting office with jurisdiction over the University of Hawaii is the Department of Health and Human Services (DHHS), 50 United Nations Plaza, Room 304, San Francisco, California 94102. Our Cost Accounting Standards Board (CASB) Disclosure Statement has been submitted to the DHHS, Office of the Inspector General, Office of Audit Services, Room 171.

6.3.2.2 Cost Principles For Educational Institutions

The University of Hawaii is an institution of higher education. As determined in FAR Subpart 31.3, Contracts with Educational Institutions, the University of Hawaii is in full compliance with the Office of Management and Budget (OMB) Circular A-21, Cost Principles for Educational Institutions, for determining the costs applicable to research and development, and other work performed by educational institutions under contracts with the Government.

6.3.2.3 Salaries and Wages

Graduate student salaries and wages at the Institute for Astronomy are approved by the UH Board of Regents and are effective until revised. The most recent graduate student monthly rates were approved effective 1 July 2003. Graduate student salaries are evaluated annually to maintain the competitive advantage of the IFA and to allow for increased cost of living in Hawaii compared to other similar domestic institutions.
Graduate students are eligible for employment at 50% FTE during the year. They are eligible for additional work during the summer. The UWO graduate student salary will be identical to the salary of other graduate students in their Physics & Astronomy department.

6.3.2.4 Fringe Benefits

The fringe benefit rates used in this proposal have been calculated based upon estimated benefit costs for direct labor personnel. The fringe benefits available to State of Hawaii and RCUH employees include retirement plan, social security (FICA) insurance, Medicare insurance, health, dental, vision, drug and life insurance plans, unemployment insurance and workers compensation. Only actual fringe benefits incurred are charged to sponsored projects.

6.3.2.5 Travel

Travel is computed from the University of Hawaii, Manoa Campus. Airfare is estimated at 21-day advance purchase fares for the most direct, economical route. Per Diem, lodging or M&IE for employees are based upon current federal per diem rates or determined by collective bargaining agreements. The University of Hawaii travel policies allow for the inclusion of other reasonable travel costs (e.g. car rentals and conference fees) and are in full compliance with Federal Travel Regulations. Estimated travel costs are based on historical charges.

6.4 Details

6.4.1 Salaries & Wages

6.4.1.1 MOPS Post-doc (Veres)

The post-doc will be the primary science interface between the MOPS software team (led by co-I Denneau who supervises the MOPS junior software engineer) and provide them science-based assessments of the quality of MOPS data products. His salary is identical to other IfA post-docs. It is important to have a trained astronomer using the data to assess its quality.

6.4.1.2 MOPS Junior Software Engineer (TBD)

The junior MOPS software engineer will be the primary engineer responsible for continued MOPS improvements and software development. We will advertise widely to identify and attract a good junior-level person and must offer a competitive salary to convince them to work and live in Hawaii. We believe that a software engineer is critical to continuing the high-level of performance we expect out of the MOPS system. It was originally developed by software engineers and uses techniques that are beyond the typical skills of most astronomers. At the moment we have only one person fully capable of managing MOPS software (co-I Denneau) but the Pan-STARRS project is training another software engineer (Denver Green) thru the end of the year. The junior software engineer described here will assume responsibility for the system once Green directs his attention elsewhere on Pan-STARRS at the beginning of 2012. We believe it is highly desirable to have 3 software engineers available to resolve problems with the system.
6.4.1.3 MOPS graduate student research assistant (Schunova)
The graduate student will assist Veres, Wainscoat on assessing the MOPS product’s data quality. It is important to have a junior scientist who can assist with tracking down frequent but minor problems that fall below the threshold of the attention of the more senior scientists. Her salary is identical to other IfA graduate students.

6.4.1.4 PS1 Observers (already employed)
The 4 PS1 observers have been employed by the PS1SC for the past few years to operate the PS1 telescope throughout the night. We believe it is critical to have good people who are well trained to operate the system on a nightly basis. Their salaries are commensurate with their experience and the salaries of observers on other telescopes in Hawaii. This grant covers 81% of their salaries in the first year and 90% in the second and third years.

6.4.2 MOPS Computer Hardware
Only about 1% of the total budget request is for new computer hardware for the MOPS system and team. The MOPS system is capable of handling the current PS1 data rate so we are requesting only a modest amount of funds to cover upgrades, equipment failures, and, if necessary, research computers for the senior co-Is, grad student or post-doc. We also anticipate that at the end of the PS1SC sky survey there will be a global data reprocessing that will require reprocessing all the historical data through MOPS at the same time the post-PS1SC sky survey begins. Processing the different data streams at the same time will require extra computing power. We do not provide detailed cost estimates for this equipment because we are currently about 1.5 years from when the new hardware would be purchased. Our request for $10K/year is based on our experience purchasing MOPS and IPP hardware over the past 8 years. The equipment will be used exclusively for the proposed research activities and not for general business or administrative purposes.

6.4.3 Travel
We request funding each year for travel to national and/or international conferences in the field of planetary sciences so that MOPS personnel can present the results of the PS1 survey and MOPS performance. In each of the 3 years we request support for 2 people to attend the AAS’s Division of Planetary Science (DPS) annual meeting – the largest planetary science meeting each year. We also request support for 2 people to attend the annual Lunar and Planetary Science Conference (LPSC) meeting in Houston in year 2. We believe that the PS1 and MOPS system performance needs to be communicated to the mostly meteoritical scientists who attend that meeting because there is a good chance that PS1 will detect another 2008 TC3-like impactor – a small meteoroid before it impacts the Earth and showers meteorites on the surface.

In accordance with section 2.3.10(c)(vi) the support for Andrea Milani’s visit to the U.S. is to assist in MOPS development but we provide no salary support. Only ‘the direct purchase of supplies and/or services that do not constitute research’ will be supported by this grant.

6.4.4 Supplies
6.4.4.1 Computer
This grant will fully support a grad student, postdoc, software engineer, who are supervised by two senior personnel. While all but the software engineer (who will not be hired till funding for this proposal is secure) currently have desktop and laptop computers we anticipate the purchase of a system for the software engineer along with the failure or necessary upgrading of one of the existing computers.

6.4.4.2 General
Each of the members of the MOPS team require peripheral devices such as storage drives, mice, extra monitors, etc., with which to perform their work.

6.4.5 Publication Charges
We will submit papers to refereed journals regarding PS1 and MOPS system performance and science. The journals sometimes require payment to support either the publication of the article itself or color figures, etc. We request funding to cover the anticipated costs.

6.4.6 Computer Support Recharge System
Computer support services are provided by the Institute for Astronomy's Computer Services Recharge System (CSRS). Costs are assessed to each project based upon an annual charge per full-time equivalent faculty or staff member. Services provided include access and use of the institute's central computer system and hardware or software support. The rates are computed annually on a consistent basis and are in full compliance with the cost principles mandated in the Office of Management and Budget (OMB) Circular A-21.

6.4.7 Other Direct Costs
6.4.7.1 Utilities
The PS1 Observatory currently uses about $7,200 per month in electricity. We are requesting 80% support for electricity usage in year 1 and 100% support for the remaining 2 years. Data transfer charges from the summit provided by Hawaiian Telcom are currently $7,820 per month. We are requesting 80% support for this cost in the first year and 100% in the second and third years.

6.4.7.2 MHPCC
The PS1 data is housed at the Maui High Performance Computing Center (MHPCC) on UH owned hardware. The current monthly operational cost (mainly electricity and cooling costs) is about $12,000 per month. We anticipate a substantial increase in this value in late 2011/early 2012 to about $20,000/month due to bringing the PS1 database online at MHPCC. We are requesting 80% support for this cost in the first year and 100% in the second and third years.

6.4.7.3 Vehicle Lease
PS1 Operations currently leases two vehicles thru the U.S. Air Force’s contract with the General Services Administration. The average cost for these vehicles including repairs
and insurance is about $1,900 per month. We are requesting 80% of the lease costs in the first year and 100% in the second and third years.

6.4.7.4 Server Maintenance
The maintenance cost for the Cisco server equipment is currently $10,380 per year. We are requesting 80% support for the hardware maintenance cost in the first year and 100% in the second and third years.

6.4.8 Administrative Recharge System
Per UH's Cost Accounting Standards Disclosure Statement filed with the U.S. Department of Health & Human Services (UH's cognizant agency) the Institute for Astronomy charges administrative support costs as direct costs due to the complex nature of its research programs and telescope operations which require a unique and highly sophisticated financial management system. IfA uses the Administrative Recharge System (ARS) to allocate administrative support costs to sponsored agreements on the basis of modified total direct costs. Because IfA allocates costs in this manner, UH negotiated with its cognizant agency a special research F&A cost rate to compensate for the direct charging of administrative support costs.

6.4.9 Indirect Costs
The Facilities and Administrative Cost Rate used in this proposal is 34.2% for On-Campus Institute for Astronomy Research for the period July 1, 2009 to June 30, 2012.
7 Special Notifications and/or Certifications

7.1 Foreign Participation & Export Control

Since our proposal includes collaborations with foreign researchers (Abe, National Central University, Taiwan; Milani, University of Pisa, Italy) the proposal guidelines require that we review our compliance with U.S. export laws and regulations, e.g., 22 CFR Parts 120-130 and 15 CFR Parts 730-774, as applicable to the circumstances surrounding their participation.

The foreigners have no formal responsibilities for this proposal. Their contribution is limited in the case of Abe to providing voluntary NEO candidate followup on telescopes available to him and, in the case of Milani, to voluntarily providing quality control assessment and improvements to his already publicly available orbit determination and ephemeris software. This proposal will not provide any software or hardware to our foreign collaborators that is not already publicly available. The only exchange involves data files containing the results of synthetic integrations of synthetic asteroids or data files containing astrometry and photometry of PS1 asteroid detections that are already publicly available through the Minor Planet Center. Thus, we do not believe that it is necessary to obtain the prior approval of the Department of State or the Department of Commerce via a technical assistance agreement or an export license.