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The Next Decade Of Solar System Discovery With Pan-STARRS

†R. Jedicke, E. A. Magnier, N. Kaiser, K. C. Chambers

Institute for Astronomy, University of Hawaii, Honolulu, HI, 96822
email: jedicke@ifa.hawaii.edu

Abstract.
The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) at the University of Hawaii's Institute for Astronomy is a funded project to repeatedly survey the entire visible sky to faint limiting magnitudes ($m_R \sim 24$). It will be composed of four 1.8m diameter apertures each outfitted with fast readout orthogonal transfer Giga-pixel CCD cameras. A single aperture prototype telescopes is achieved first-light in the second half of 2006 with the full system becoming available a few years later. Roughly 60% of the surveying will be suitable for discovery of new solar system objects and it will cover the ecliptic, opposition and low solar-elongation regions. In a single lunation Pan-STARRS will detect about five times more solar system objects than the entire currently known sample. Within its first year Pan-STARRS will have detected 20,000 Kuiper Belt Objects and by the end of its ten year operational lifetime we expect to have found 10^7 Main Belt objects and achieve ∼90% observational completeness for all NEOs larger than ∼300m diameter. With these data in hand Pan-STARRS will revolutionize our knowledge of the contents and dynamical structure of the solar system.

Keywords. Keyword1, keyword2, keyword3, etc.

1. Pan-STARRS Overview

The conceptual design of the Pan-STARRS system derives from a desire to survey the sky as deeply, rapidly and inexpensively as possible. Relatively simple technological and economic arguments suggest that

the minimum cost for a surveying system is achieved with telescope mirrors in the range of 1.5m to 2.5m diameter. Simply put, it is more cost effective to build more small telescopes to reach the same effective limiting magnitude and sky-coverage as a massive system due to the fact that duplicating a small system increases costs linearly while the cost of a single large system increases as a power of its light gathering ability. Another major benefit of a distributed aperture system is the reduced time to deployment over a monolithic system with equivalent etendue. Thus, Pan-STARRS opted to develop a design for a coordinated set of four small telescopes with the capability of a large synoptic survey system.

A prototype single Pan-STARRS telescope (PS1) on Haleakala is nearing completion and is expected to start survey operations in mid to late 2007. It is designed to act as a test-bed for the commissioning, testing, and calibration of the Pan-STARRS hardware and software in anticipation of the full (four aperture) Pan-STARRS array. PS1 uses a 1.8m primary mirror to image a roughly 7 square degree field on a 1.4 Gigapixel CCD camera. With 0.26 arcsecond pixels, the images from PS1 will be well-matched to the sub-arcsecond seeing of Haleakala. The large entendue of PS1 will make it the most

† for the Pan-STARRS team.

efficient survey telescope for the near future. The PS1 Survey Mission is expected to last 3.5 years, and will produce about 1.8PB of raw image data.

The PS1 Survey Mission will consist of multiple survey components, including a very large area survey covering three quarters of the full sky (the 3π survey) and targeted fields observed frequently and repeatedly for both extensive temporal coverage and depth. A major driver for the observing strategies is to efficiently detect solar system objects including potentially hazardous asteroids. The telescope will use 4 filters very similar to the Sloan griz set and a y filter at the reddest end of the camera sensitivity to exploit the high quantum efficiency of the detectors at 1 micron.

Figure 1. The prototype Pan-STARRS telescope installed near the top of Haleakala, Island of Maui, Hawaii. All the optics are in place, the dome is operational and first light has already occurred. Installation and testing of the OTA camera (near the center of the primary mirror) is the next step.

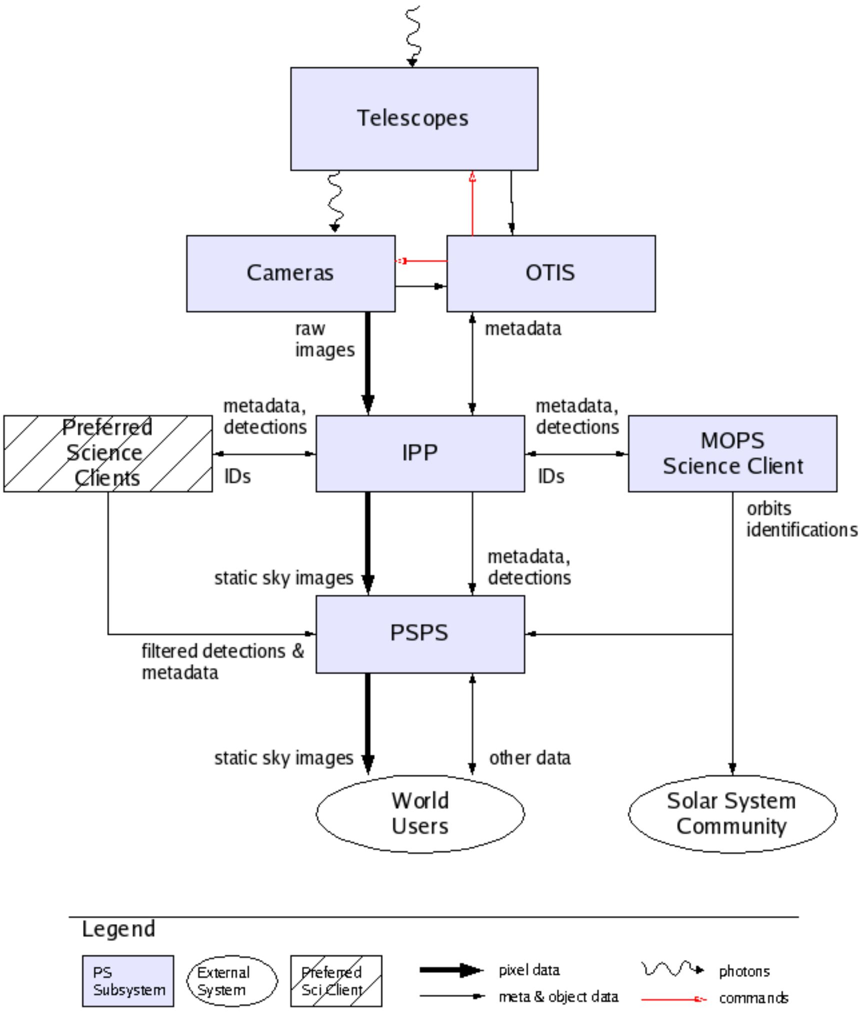

Figure 2. PS1 concept of operations.

The primary enabling technology for Pan-STARRS is the development at the Institute for Astronomy (IfA) of Orthogonal Transfer Array (OTA) CCDs Tonry *et al.*(2002). These CCDs boast an amazing set of characteristics including fast readout (a few seconds for a 4K×4K array), low read noise (about 5 e^-), superb response at long wavelengths (40% QE at 1μm) and low cost. Perhaps the most innovative features of the OTAs are their ability to move charge between pixels in both directions on the CCD and to read out sub-arrays on the CCD (called cells) as an image is being acquired. These two features in combination allow a poor mans first order correction to both atmospheric and mechanically induced image motion. The ∼20% reduction in the PSF width for point sources provides an important increase in limiting magnitude and source identification. On Mauna Kea, we expect to acquire images with 0.5" width in median seeing of 0.6".

Figure 2 shows the high level concept of operations for the PS1 system. We expect that it will be representative of PS4 operations as well but will modify the actual concept based upon our experience with PS1. Major elements represented in fig. 2 are already well developed, with sub-system completeness generally decreasing from top to bottom.

The telescope is controlled by the Observatory Telescope and Instrumentation System (OTIS). OTIS is responsible for monitoring the weather and sky conditions, deciding on an image-by-image basis which field to obtain next, issuing telescope and dome commands, etc. Metadata collected by OTIS are made available for image processing and science analysis

Each of the four apertures has its own 1.44Gpix camera. The camera system is responsible for implementing the OTA image correction. A few percent of the cells containing bright stars that would otherwise saturate or bleed into the system are read out at about 20Hz. Their centroids are calculated in real time and their positions are used to determine appropriate (x, y) offsets to the positions of the charge in all the other cells in the camera. Finally, the entire image is read out and passed to the Image Processing Pipeline (IPP).

The IPP is responsible for all the image reduction and preliminary analysis (see §2). It identifies known stars in the field to solve for the astrometric reference for the image, measures the flux from each object in the field, characterizes the shape of all detections, adds the current image to a static-sky image that gradually builds a deep representation of the non-moving objects on the sky, warps and convolves the existing static-sky image so that it may be subtracted from the current image and leave only transient objects in the difference image and, finally, detects and characterizes transient sources in the difference image. The set of all transient detections (stationary, moving and false) are passed to the Moving Object Processing System (MOPS, see §3) for asteroid and comet detection.

The Pan-STARRS published science products system (PSPS) is the database of detections and images produced by the IPP. It is the window into Pan-STARRS for the world and the repository of all information for internal access by Pan-STARRS users.

The Pan-STARRS concept of operations (fig. 2) allows for many preferred science clients (PSC). These software sub-systems obtain their data from the IPP and perform analysis-specific tasks for a particular science goal. PS4 will have many PSCs including supernovae, extra-solar planet, weak gravitational lensing and high-z galaxy clients. The only existing PSC for PS1 and PS4 is the MOPS that is funded through the development and construction costs as a recognized major part of the core Pan-STARRS goal of detecting NEOs and other solar system objects.

2. Image Processing Pipeline

The Pan-STARRS PS1 Image Processing Pipeline (IPP) performs the image processing and data analysis tasks needed to enable the scientific use of the images obtained by the Pan-STARRS PS1 prototype telescope. The primary goals of the IPP are to process the science images from the Pan-STARRS telescopes and make the results available to other systems within Pan-STARRS. It is also responsible for combining all of the science images in a given filter into a single representation of the non-variable component of the night sky - the 'Static Sky'. To achieve these goals, the IPP also performs other analysis functions to generate the calibrations needed in the science image processing, and to occasionally use the derived data to generate improved astrometric and photometric reference catalogs. It also provides the infrastructure needed to store the incoming data and the resulting data products.

Like other large-scale surveys (e.g., the Sloan Digital Sky Survey or the 2 Micron All-Sky Survey), end users will have access to derived data products, not the raw image data stream. The IPP will perform the individual image calibrations, image combinations, and object measurements needed to characterize the astronomical sources detected in the images. During clear, dark nights, the PS1 telescope will produce images at a sustained rate of about one 3GB image every 45 seconds for periods as long as 10 hours. The IPP needs to perform the data processing with a high enough throughput to keep up with the raw image data. The resulting data products and the extensive supporting metadata stream will be made available to the other components of the project including the Published Science Products System (PSPS) which will, in turn, make the data products available to users via a database and sophisticated query mechanism. Other science clients performing additional interpretation of the science data products will also receive subsets of the full IPP output data stream.

The IPP receives data from two Pan-STARRS subsystems: the Camera, from which it receives the large volume of image data, and OTIS (Observatory, Telescope and Infrastructure Subsystem), from which it receives metadata describing the images and the environmental conditions. The users of the IPP output are all systems internal to the Pan-STARRS project. They consist of: 1) The Preferred Science Clients, which receive specified data products on short timescales. 2) The Moving Object Processing System (MOPS) described in §3 that receives the detections of all transient objects. 3) The Published Science Products Subsystem (PSPS), that receives all data products of interest to the community external to the Pan-STARRS data processing systems and will act as the long-term archive and publishing clearinghouse.

The IPP performs several types of data analysis in a regular fashion. The most obvious of these is the science image analysis, from which the measurements of individual astronomical objects are actually derived. In preparation for this critical function, the IPP must also analyze the calibration images needed by the science image analysis. Downstream from the science image analysis, the IPP must perform data calibration on the collection of object detections, yielding improved calibrations and improved reference catalogs for astrometry and photometry. At 5-σ the astrometric floor is expected to be about 0.1" while the photometric floor at the same S/N should be about 0.1 mags (both improve with S/N).

The IPP science image analysis is separated into two major stages: the analysis of individual images and the analysis of groups of images taken of the same portion of the sky. The individual images are analyzed independently as they arrive from the telescope where standard image detrending steps (bias, flat, etc.) are performed. Objects are detected in the images using customized software developed by the IPP team (the image analysis software will eventually be publicly available). Stars and non-stellar objects are distinguished, but only limited effort is spent at this stage on characterizing the extended sources. Brighter stars are the used to perform astrometric and photometric calibrations. In the second major stage the images which correspond to the same portions of the sky are combined. Several image combinations may be performed. Sets of individual science images may be combined into a single, high-quality image which has been cleaned of cosmetic defects. Comparison between this image, or the individual images, and an archival reference image of the same location (the Static Sky image) may be performed. Image difference techniques are used to detect the variable, transient, and moving sources. Sources identified in difference images are passed to the Moving Object Processing System (described below) as a catalog list. Finally, the new images may be combined with the Static Sky image in order to improve its signal-to-noise.

Additional science image analysis is performed on the Static Sky images. It is in this stage that detailed analysis of the shapes of extended objects is performed. In the Static Sky analysis, the data from all five filters will be analyzed at the same time to improve the signal-to-noise for fainter sources. Common parameters such as the location of the galaxy may be fit to a single value in all filter images.

The IPP is also responsible for generating a high-quality photometric and astrometric (P&A) reference catalog from the collection of measurements of the astronomical sources. As the images are analyzed, the information about each object is supplied to the IPP object database software called DVO (the Desktop Virtual Observatory). Several programs interact with this database to iteratively improve the calibration of the individual images and to update the astrometric and photometric reference catalog.

The P&A analysis can be viewed as a very large least-squares problem, in which the astrometric or photometric parameters of the images are solved to minimize the residuals for individual objects, while the positions and magnitudes of individual objects are adjusted to minimize the residuals for individual images. It is a two step process where the first pass obtains the linear-only astrometric solution for each the CCDs independently. In the second pass the CCDs are treated together to solve for the camera distortion and high-order terms for each chip. Tests of this process with the CFHT's Megacam and CFH12K cameras have realized 10mas astrometric performance. Those cameras have pixel scales of 0.19" and 0.21" respectively, comparable to the pixel scale for the PS1 camera.

The P&A analysis will likely be limited to the objects that have been observed with sufficient signal-to-noise but the resulting image parameters can then be used to characterize all objects in the images. A natural consequence is that the objects that have significant residuals even after the iterations have run their course can be identified as photometric variables or objects with detectable proper-motion and/or parallax. Images which were obtained under less-than-ideal conditions will also be flagged and may be excluded from this analysis.

The IPP image analysis tasks are well suited to parallel processing. Not only are individual images processed independently, but most of the computational effort for each of the chips of the mosaic camera may be processed without reference to the other chips. The analysis of different patches of the sky may also be performed independently.

3. Moving Object Processing System

Pan-STARRS+MOPS (Moving Object Processing System) will be the worlds first integrated asteroid detection, linking, orbit determination and database system. Combining the processes provides Pan-STARRS a tremendous advantage in sky area coverage because it can spread the requisite number of detections over many nights with a concomitant increase in the number of NEO discoveries. Furthermore, by retaining control over all the processes Pan-STARRS can determine the efficiency of the entire sub-system as well as the efficiency of every step. This capability is critical to monitoring the MOPS performance and de-biasing the science data to account for observational selection effects.

Figure 3 provides a high level concept of operations for the MOPS. Input consists of image meta-data (e.g. boresight, limiting magnitude, filter) and all source detections with $S/N>3$ from the IPP's difference images as described above. This includes apparently stationary transients since they may be very distant slow moving objects, and also those trailed detections consistent with being images of nearby fast moving objects.

The combinatoric problem of properly linking detections of the same object observed on a few nights over a period of a couple weeks could be computationally expensive. On the ecliptic and to a limiting magnitude of $r\sim24$ we expect that there will be about 250 real moving objects per $\deg^2$ or almost 2000 asteroids and comets per single Pan-STARRS field. Asteroid sky-plane density drops quickly off the ecliptic while the rate of false detections remains constant. At 5-σ we expect a maximum of a 1:1 ratio of false:real detections on the ecliptic (i.e. $\sim$2000 false 5-σ detections per field) while at 3-σ we expect

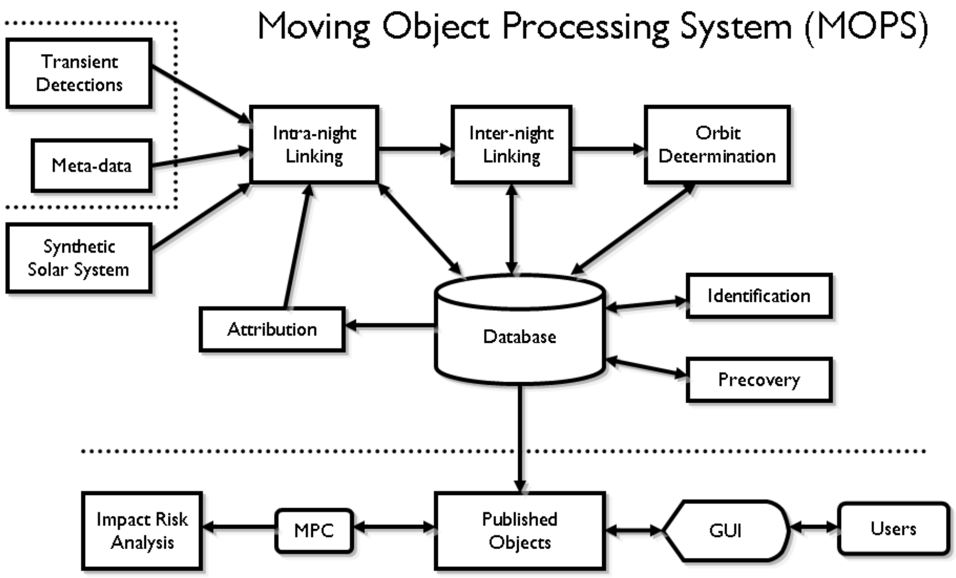

Figure 3. Moving Object Processing System concept of operations. Data in the upper left region surrounded by dotted lines is provided by the IPP. Systems below the horizontal dotted line are not part of the MOPS.

about 200,000 false detections per field or a false:real ratio of about 100:1! Even so, we expect that the 5-σ MOPS database(s) will require only about 2TB of disk storage including a full backup and other overhead requirements. The 3-σ data will probably not be stored in a relational DB but rather in compressed flat files on a distributed file network.

The current survey strategy for solar system objects is to obtain two images of each field on a night separated in time by a transient time interval (TTI) of about 15 to 30 minutes. Roughly the same fields are visited 3× per lunation. We envisage a PS1 survey strategy Chambers *et al.*(2006) that combines a photometric & astrometric survey, a medium-deep survey and a solar system survey in an efficient manner that will allow ∼55% of surveying time to be utilized in a cadence suitable for linking solar system objects. Each of the three visits (two images) will be obtained in a different filter (g, r and i) with exposure times arranged to obtain the same limiting depth for a solar colored object (equivalent to V∼23 in a 38s exposure in r). An additional ∼5% of surveying time will be devoted to surveying in the 'sweet-spots' Chesley & Spahr(2004), the sky within about 10° of the ecliptic and with solar elongation from 60° to 90°. The sweet-spot regions will be covered in either r or i, whichever provides us the best limiting magnitude for NEO detections. Figure 3 shows a single lunation of surveying in a pattern similar to that envisioned for PS1. It is clear that the sweet-spots are particularly rich in NEOs due to looking along the Earths orbit where Potentially Hazardous Objects (PHOs with a minimum orbital impact distance with the Earth of <0.05AU) must pass.

It is the responsibility of the MOPS to identify candidate moving object 'tracklets' in

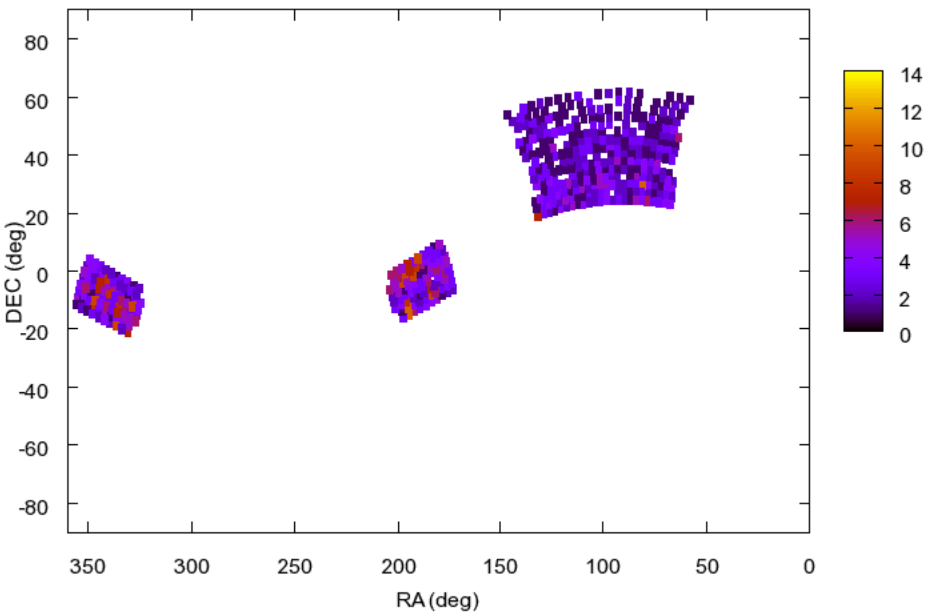

Figure 4. Sky-plane density of NEOs detected in a single lunation by PS4. The opposition region is the large area near 100° RA and the other areas represent the morning and evening sweet spots.

the images acquired within a TTI on each night. A tracklet is composed of detections that are within an angular separation and position consistent with their elongation and orientiation with respect to one another. The detections are those sources identified in difference images by the IPP as described above. The elongation of the detections is not used to identify moving object candidates, only to verify that the detections within a candidate tracklet have consistent motion vectors. Thus real tracklets are distinguished from spurious false tracklets merely by the spatial proximity and shape consistency of the detections within the tracklet *and* by the ability to link tracklets obtained on separate nights into tracks consistent with a heliocentric orbit (as described below).

Our efficiency (percentage of real tracklets that are properly identified) and accuracy (percentage of identified tracklets that are real) for creating tracklets Kubica *et al.*(2006) is essentially 100% as determined from a realistic solar system model and survey simulation. All known objects that might appear in each field are associated with identified tracklets when available (a process known as attribution). Tracklets that can not be associated with known objects are stored for future use.

Every time a new TTI image pair is acquired, the MOPS automatically searches the meta-data database of images acquired in the past 14 days to determine if there are 3 or more nights of images including the current image that might contain unknown moving objects that could be linked together. When a multi-night set of TTI image pairs are available the MOPS extracts all un-attributed tracklets from those images and attempts to link them together into candidate tracks that might be consistent with a newly identified solar system object. The combinatoric difficulty in creating tracks has been solved using a variable kd-tree algorithm Kubica *et al.*(2006). The formation of tracks does not incorporate any orbit information. By implementing a few passes through the data appropriate for different classes of solar system objects we have achieved >99% efficiency in creating tracks for objects in a realistic but synthetic survey. The accuracy of track formation is about 0.3% but this percentage is relatively unimportant as long as the incorrect tracks can be discarded through an orbit determination attempt.

Once tracks have been created each one must be tested for compatibility with a heliocentric orbit by attempting an initial orbit determination (IOD). Tracks for which the IOD provides a suitably low residual with respect to all the detections are then passed to a differential orbit determination routine (OD) that attempts to fit the orbital parameters to the observations and further reduce the residual while improving the orbit.

We are currently studying the IOD and OD efficiency at producing useful orbits. The orbits do not necessarily have to be 'correct' if they can be used to link the object to future (attribution) or past (precovery) detections. E.g. for slow moving objects we may choose to use an IOD or OD with fixed eccentricity to allow convergence in the orbital solution. Our preliminary indications are that we can achieve nearly 100% efficiency for orbit determination of correctly linked tracks with <1% contamination by orbits obtained with false linkages.

We have usable prototype code in place for moving object attribution and also precovery detection identification but have not yet tuned their performance. Similarly, the process of "orbit identification", in which the same object may be separately identified and linked in different apparitions without it being possible to attribute or precover mutual detections, but where their identity may be discovered through the similarity of their orbit elements, also exists in prototype form.

The MOPS incorporates efficiency determination software (EDS) directly into its architecture. The EDS requires a high-fidelity solar system model containing $> 10^7$ synthetic asteroids and comets that we have developed for this purpose. The model contains realistic orbit and size distributions for all the objects including tri-axial ellipsoid shapes, random pole orientations and a spin period distribution. Each time new detections are provided by the IPP the MOPS generates synthetic detections that should appear in the image according to the solar system model and the meta-data from the IPP (e.g. limiting magnitude, trailing effects, chip gaps). The synthetic detections are injected into the MOPS pipeline and analyzed at the same time and in exactly the same manner as the real detections. Since we know what synthetic detections went into the MOPS we can monitor their progress through the system in nearly real-time and determine if there is a problem with any MOPS sub-system. The ability to determine the overall efficiency of the system is critical to correcting the data for observational selection effects.

4. Pan-STARRS and the solar system

The prototype Pan-STARRS telescope on Haleakala will yield the best measurement of all asteroid and comet populations to date by providing a sample that is much larger than the entire data set currently in hand and, more importantly, doing so with a single well-calibrated detection system. This will dramatically decrease the current errors in the orbit and size distributions of all populations (especially at small sizes).

Working radially outwards from the Sun we speculate below on the impact of PS1 on our knowledge of the solar system's small bodies.

Pan-STARRS has been designed to be capable of surveying at low altitude allowing detections of moving objects at small solar elongations especially in the range from 60° to 90°. This region of the sky is important to the discovery of PHOs Chesley & Spahr(2004) and objects entirely Interior to the Earth's Orbit (IEO) so we expect that the number of known PHOs and IEOs will increase dramatically in the next few years. These observations will thereby allow a much better characterization of the Earth impact risk. The IEOs are particularly interesting because they provide a sensitive test on contemporary models Bottke *et al.*(2002) of transport of asteroids from the MB into NEO space.

Collapsing the error bars on the size and orbit distribution is also important because it allows a better tuning of the capabilities for future NEO surveys. For instance, it is possible that the impact risk is larger than currently estimated because there may be local enhancements in the orbit distribution of PHOs. The fact that Tunguska (a once in a 1000 year event) and Apophis (a once in a tens of thousands of years event) occured within a century of one another makes it reasonable to speculate that the orbit distribution of NEOs is not as smooth as current models Bottke *et al.*(2002), Stuart & Binzel(2004) would suggest. PS1 will resolve these issues.

PS1 will extend the completeness limit for objects in the entire MB (to its outer edge at about 3.3 AU) from the current value of about absolute magnitude 14.5 to 18 (complete for all objects >1 km diameter in the MB). This sample should resolve many open disputes about the size distribution of these objects e.g.]Gla06,Ive01. We expect that this will allow the identification of dozens of new young asteroid families and with the addition of five filter measurements we will be able to refine space weathering rate estimates Nesvorný *et al.*(2002). Simple extrapolation of the discovery rates of MB comets Hsieh & Jewitt(2006) suggest that we may identify hundreds of this new class of objects. Perhaps most interesting of all is the opportunity of identifying collisions between MB objects too small to otherwise be observed. A collision between a 100m and 10m asteroid might create a dust cloud that lasts sufficiently long to be identified as a 'transient moving object'. The collision rates in this size range Bottke *et al.*(2005) imply that PS1 might identify one such event per month but this estimate is almost entirely dependent upon how long the dust clouds remains at an optical depth greater than one.

The Trojan regions of all the planets will be surveyed to a consistent limiting magnitude and with known efficiency allowing for a detailed analysis of the stability of these regions and a resolution of the issue of different numbers of objects in the Jovian L4 and L5 regions. Similarly, we will obtain a far larger sample of Centaurs than currently exists allowing for detailed measurements of the transport of objects from the Trans-Neptunian region into giant-planet-crossing orbits.

The number of TNOS will increase by at least an order of magnitude. The impact that these new objects will have on our understanding of the structure of the Kuiper Belt will be incredible. If recent estimates of the number of small TNOs Chang *et al.*(2006) hold, they imply that collisions between TNOs will happen frequently and PS1 may be able to detect them as was argued for MB asteroid collisions above. If our solar system formed in a dense star forming region and interacted with another system it is possible that there exist retrograde orbit TNOs. The MOPS has been designed to identify objects moving in any direction so that if there are retrograde TNOs above the PS1 detection threshold they should be identified as such.

The MOPS is also being designed to identify extremely slow moving objects. Those objects that appear to be stationary in two images acquired on the same night only 15-30 minutes apart, yet move from night to night over the course of 7-10 days. We estimate that the MOPS is capable of detecting objects moving almost as slowly as Barnard's Star. Thus, if there exist large objects well beyond the orbit of Pluto we will find them. PS4 will be sensitive to an Earth sized object out to 620 AU Jewitt(2004).

New frontiers will open in the study of comets as the number of objects and the temporal coverage increases dramatically. Since PS1 will revisit the same location on the sky many times in different filters and identify comets when they are much further away than existing surveys, it will be possible to study the detailed morphological evolution of comets as a function of heliocentric distance and other physical or dynamical characteristics.

One of the many exciting possible new discoveries is that of identifying unambiguous interstellar asteroids or comets. While estimates and limits on the volume density of these objects vary greatly it has been estimated Jewitt(2004) that PS4 will either detect a few interstellar interlopers or set the best limit to date on their number density. The scientific potential of such a discovery are incredible as spectroscopic followup of the object could reveal the chemical and/or mineralogical composition of objects from another solar system.

Finally, after a number of years of surveying PS will obtain perhaps a hundred(s) of observations of some bright asteroids. At sufficiently high S/N the PS photometric error will be on the order of 0.01 mags, allowing the light curve inversion techniques of Kaasalainen(2004) to be applied in order to determine the spin period, pole orientation and even shapes of hundreds or thousands of asteroids. At the current time spin periods are known for about 1000 asteroids, pole orientations for just over 500 of them, and shapes for only a handful that have been close enough to obtain radar information or that were spacecraft targets.

5. Conclusion

The PS1 and MOPS will be the first integrated asteroid and comet discovery, linking, orbit determination and database system. We have developed new algorithms to handle the combinatoric problem of linking detections on a single night and between nights within a lunation. We have developed the first comprehensive model of the solar system including over 10^7 objects that might be discovered by Pan-STARRS during the course of its ten year operational lifetime. The MOPS is the first asteroid and comet linking system to embed an efficiency determination and monitoring system. By the end of 2007 the PS1 system should be discovering more asteroids each month than all other surveys in the world combined. When PS4 begins operations it will identify in a single month more asteroids than are currently known.

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