Asteroid Detection with the Pan-STARRS Moving Object Processing System

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ABSTRACT

We present the first asteroid discoveries by the Pan-STARRS prototype telescope (PS1) using the Moving Object Processing System (MOPS). The MOPS was designed to be capable of detecting fast moving objects whizzing by the Earth as well as those moving as slowly as the fastest proper motion stars. We will discuss the design of the MOPS and its efficiency, accuracy, and reliability as determined from long term realistic simulations with synthetically generated objects in the presence of false detections. Our simulations with a synthetic but realistic NEO population indicate that PS1 will discover more of these hazardous objects in its 3.5 year mission than all existing surveys have identified since asteroids were first discovered more than 200 years ago. In particular, we will show that PS1 has a high efficiency for discovering objects that will actually impact the Earth in the next 100 years.

INTRODUCTION

The Institute for Astronomy at the University of Hawaii has completed construction of a 1.8 m telescope for wide-field optical astronomical surveying—the prototype for the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), called PS1. PS1 provides state-of-the-art capability in its gigapixel camera (GPC) with 7deg^2 imaging area and 1.4 billion pixel detector which achieve a pixel spacing of 0.26 arcseconds on the sky and nominal absolute astrometric accuracy baseline of 0.1 arseconds. The full-blown version of Pan-STARRS, a four-telescope configuration called PS4 scheduled for operations in 2013, is expected to achieve an absolute astrometric accuracy of 0.01 arcseconds RMS [1].

The Pan-STARRS Moving Object Processing Subsystem (MOPS), the asteroid detection pipeline for PS1, has been under development since 2004. A top-level design requirement of MOPS is to identify and catalog 99% of potentially hazardous objects (PHOs) greater than 1 km in diameter and 90% of PHOs greater than 300 m [1]. During MOPS development, we have characterized MOPS's performance in great detail, specifically its ability to catalog near-earth objects (NEOs) and potential impacting asteroids, using a high-fidelity synthetic solar system model containing over 15M synthetic orbits of various populations.

While the development and construction of PS1 was performed by the University of Hawaii's Institute for Astronomy and funded by the United States Air Force Research Laboratory (AFRL), subsequent operation of the PS1 telescope and its 3.5-year survey is managed by the PS1 Science Consortium (PS1SC), a multi-national association of institutions seeking science opportunities within PS1 data for various astronomical disciplines.

MOVING OBJECT PROCESSING SYSTEM

The Moving Object Processing System (MOPS) science client of the PS1 Image Processing Pipeline (IPP) accepts catalogs of transient detections, or (*time, RA, declination*) coordinates, from image difference data reduced by the IPP. The PS1 observing cadence ensures that over a single night, pairs of images are taken a the same telescope boresight separated by a *transient time interval* (TTI), typically 15-30 minutes. A typical main-belt asteroid with a sky-plane velocity of 0.2 deg/day at opposition will move 7.5 arcsec (29 pixels) during a 15-minute TTI [1]. In a typical image on the ecliptic plane, MOPS will encounter 250 moving objects per square degree when operating at PS1's limiting magnitude of R=22.7, or around 1750 per PS1 exposure [2].

During a typical night, PS1 will acquire around 500 exposures. The PS1 survey is a complicated balancing act serving various science missions, but the parts of the survey that will serve asteroid discovery are the 3π astrometric/photometric opposition survey and the low-solar-elongation (60-90 degrees from the sun) "sweetspot" survey. The 3π opposition survey will cover 3π steradians on the sky in 60-degree wide stripes in declination each lunation in five different filters, *g, r, i, z,* and *y*. Thus over 6000 deg^2 of opposition sky will be be available for asteroid discovery. The sweetspot survey occurs at low-solar-elongation regions (60-90 degrees from the sun) shortly after sunset or before sunrise. These regions are called the evening and morning sweetspots, and are selected because of their enhanced density of PHOS due to geometric configuration [3].

MOPS assembles associations of detections from TTI pairs into *tracklets* [4], which can be thought of as (*position*, *velocity*) pairs for potential real objects. In assembling tracklets MOPS makes no assertion whether a tracklet is composed of detections from real asteroids or from other sources of transient detections such as Poisson photon noise in the detector or spurious artifacts from bad image subtraction. MOPS is designed to cope with a nominal false detection rate equal to the rate of real objects on the ecliptic at a 5σ significance (approximately 1500 per deg^2) [1], but in practice is able to succeed in the presence of higher rates of false detections, typically 10-20X.

Given sets of tracklets acquired over multiple nights, MOPS then constructs linkages of tracklets called *tracks* that follow nominally-asteroidal motion on the sky within the astronomical uncertainty of the track's constituent detections [4]. These tracks are then evaluated individually by attempting to compute a differentially corrected orbit, and if the orbital solution converges to a high-enough quality orbit, the track is considered to be a real object and preserved in the MOPS system as a *derived object* for future processing. Studies by Chesley and Spahr show that at the expected PS1 astrometric accuracy of 0.1 arcseconds RMS, a set of three tracklets spread over eight days and spaced by four days is sufficient to produce a high-quality orbit suitable for recovery of a main-belt asteroid or NEO in a previous or successive lunation [3].

After a derived object is created, MOPS attempts to associate future tracklets with existing derived objects before attempting to use them to create new derived objects. When operating on tracklets from newly acquired TTI field pairs, this process is called *attribution*. After all tracklets and tracks for a night are processed, an identical operation is performed backwards in time on MOPS historical data, called *precovery*. Via attribution and precovery, MOPS is able to refine the accuracy of a derived object's orbit by extending the arc (information content) of an orbit and increasing the number of detections contributing to the orbit.

In some cases, usually a poorly determined orbit, MOPS's prediction for a derived object's position in a field is insufficiently accurate that MOPS is not able to locate the correct tracklets with which to perform attributions. When this happens it is possible that MOPS will create a second derived object for the same real object if the object is seen the requisite three times during a lunation at the nominal MOPS cadence. MOPS has a procedure called *orbit identification* in which derived objects with similar orbital characteristics are compared; for pairs of objects close in orbital element phase space, an orbit determination is attempted using the combined set of detections from both objects, and if the orbit converges, one of the derived objects is retired and its tracklets (and thus detections) are assigned to the other derived object.

MOPS stores all of its astronomical objects—exposure metadata, detections, tracklets, derived objects and orbits, and relations between these objects—in a relational MySQL database. MOPS further stores a "paper-trail" history of derived objects so that the creation and subsequent modification of a derived object via attribution, precovery or orbit identification can be analyzed by scientists or data mining software.

MOPS does not attempt to use existing catalogs of known objects, such as the Minor Planet Center (MPC) asteroid database, when processing detections from the PS1 IPP. The motivation for this idependence from existing catalogs is to minimize the effects of (sometimes unknowable) biases in the source detections for these catalogs. Analysis of the MOPS dataset against known object catalogs is left for future study by PS1 Science Consortium project scientists. Along these lines, MOPS employs "add-on" software to decorate its tracklets with information obtained from external processing as a rudimentary method of associating MOPS data with external catalogs. Currently, the MOPS team employs a software package called KNOWN_SERVER (KS) by Knežević that compares predictions of the MPC numbered and multi-opposition object catalogs against an input set of tracklets and can assess the debiased astrometry of the input detections against the catalogs.

MOPS SOLAR SYSTEM SIMULATION

MOPS employs a population of synthetically-generated orbits and absolute magnitudes called the MOPS Synthetic Solar System Model (S3M) [5]. These synthetic objects are used to populate simulated fields with observations for MOPS testing, and are also integrated into the live MOPS processing stream so that instantaneous system efficiency and accuracy can be ascertained. The full S3M consists of over 14M objects consisting of several different sub-populations of objects whose size-frequency distribution are known to varying accuracy. Optional S3M populations of unrealistic or extremely rare objects exists so that the full phase space of MOPS capability can be tested; for example earth-impactors, as-yet undiscovered retrograde main-belt asteroids or interstellar objects on hyperbolic orbits.

Table 1. MOPS Synthetic Asteroid Population

Population	**Number**
NEOs	250,000
Main Belt	13,500,000
Trojans	180,000
Centaurs	60,000
Trans-Neptunian	70,000
Scattered Disc	20,000
Long-period comets	9,400
Short-period comets	80,000
Hyperbolics	8,000
Impactors	10,000
Total	**14.5M**

The populations of MOPS synthetic asteroids is shown in Table 1. The NEO population is based on the Bottke et al. NEA population model [6], and the Main Belt population is based on current known orbital distributions of Main Belt asteroids, scaled to reproduce a sky-plane density of approximately 250 objects/deg^2 in the ecliptic. Impactors were synthesized by results from Chesley and Spahr [7]. Other populations were developed similarly, with some selection criteria for observability in the case of distant populations (Trans-Neptunian, Scattered Disc objects) [5].

MOPS PERFORMANCE

During MOPS development, we have characterized MOPS performance by running full-scale synthetic simulations for many lunations. Typically we select a set of fictitious but realistic telescope boresights generated by a survey tool, then compute “fuzzed” positions for objects in our solar system model within these fields. The positions are smeared by spreading them astrometrically and photometrically using a parameterization consistent with expected PS1 astrometry and photometry.

After generating fuzzed positions for all boresights in a test simulation, we process the detections through the MOPS pipeline as through they were real detection data. After the data are processed, we can then compute efficiency of the pipeline by MOPS’s ability to create derived objects for all objects that appeared in the data at the MOPS cadence, or at least three nights within a lunation of the simulated survey. Note that objects may appear in the simulated detection data but can deemed unrecoverable because move out of the observing area, or fall below the simulated magnitude detection threshold. We define efficiency as the number of objects recovered by MOPS divided by the number of objects that appear in the data at the nominal MOPS cadence [1].

We find that with simulated data MOPS is easily able to meet top-level requirements in its ability to recover solar system objects. Table 2 summarizes MOPS performance for a single month of MOPS processing using a fictitious observing strategy nominally similar to PS1's expected survey strategy [8].

Table 1. MOPS efficiency recovering synthetic orbits during a single month from a full-scale simulation with PS1 initial astrometry

Population	Number	Efficiency (%)
NEOs	377	92.4
Main Belt	244,284	93.9
Trojans	1,240	90.8
Centaurs	1,423	97.9
Trans-Neptunian	1,506	99.3
Scattered Disc	275	99.3
Long-period comets	188	90.4
Short-period comets	243	94.6
Total	**249,536**	**93.9**

Extensive simulation work by Granvik show that a simulation of four years of PS1 operations will produce discoveries of 8,000 NEOs, including 1,300 potentially hazardous asteroids (PHOs) with absolute mag $H < 22$ [9]. In addition, there is a 10% chance that PS1 will detection an object like 2008 TC_3, a several-meter diameter earth impactor that stuck earth 20 hours after discovery. Further work by Vereš et al. using a population of 110,000 earth impacting asteroids show that during its 4-year survey, PS1 could identify 85% of all 1 km diameter objects that will impact the earth over the next 100 years [10].

PS1 RUN 3

In June 2009, PS1 began science observations with the PS1 telescope. While the survey is not yet operating at full capability and scheduling efficiency, enough data were acquired to detection thousands of known objects within the PS1 data and to submit observations for a handful of discovery candidates to the MPC. Our first high-quality dataset from PS1, called Run 3, spans roughly one month from June-July 2009, over 18 distinct nights, covering the sky from approximately 270 to 300 degrees in RA and -30 to 0 degrees declination. Table 2 shows the number of visits acquired for various portions of sky for Run 3. Recalling that MOPS requires six visits (three nights) in order to obtain an orbit, it is apparent that due to poor overall coverage and especially lack of coverage near the ecliptic (-23 degrees declination), Run 3 is far from optimal for asteroid discovery.

Table 2. Run 3 cumulative surveyed area by number of visits

# Visits	Total Area
2	24 deg^2
4	526 deg^2
6+	226 deg^2

Fig. 2 shows the orbital eccentricity and semi-major axis for 151 derived objects (three-night orbits) found by MOPS in the Run 3 data whose RMS positional residuals falls below 0.2 arcseconds. The dark circles indicate high-quality derived objects that have no matching object in the Minor Planet Center (MPC) object database and thus are likely new discoveries. Previous simulations indicate that at current densities of false objects in the Run 3 data, derived objects above the q=1.3 line (NEOs) are likely false positives. In order to submit these derived objects to the MPC with short orbital arcs (usually < 10 days), we visually inspected all NEO orbits to confirm this; unfortunately all were indeed false.

We further analyzed the Run 3 detections by attempting to associate individual tracklets with objects in the MPC catalogs of numbered and multi-opposition asteroids using the KNOWN_SERVER software provided by the Knežević and the OrbFit consortium for PS1. In Run 3 we associated 4323 different known objects over 5350 tracklets (10,700 detections). Fig. 3 shows the distribution of debiased positional residuals of the PS1 detections of these known objects. Encouragingly, we see that the residuals show no RA or declination bias and exhibit an RMS of 0.12 arcseconds in RA and 0.14 arcseconds in declination, among the highest-quality astrometry in the MPC detection catalog [11].

We attempted to characterize our detection and tracklet creation efficiency by running a separate simulation using the boresights from Run 3 and a synthetic object population consisting only of the orbits and magnitudes of the numbered and multi-opposition asteroid catalogs. This simulation gives us an estimate of the total number of tracklets of known object we expect to find in Run 3. Fig. 4 shows the distribution of found and predicted detections in Run 3 exposures acquired in *r* filter, indicating a loss of 68%. While the MOPS team has not performed further quantitative analysis of this loss, the loss is consistent with an estimated 80% fill factor of the PS1 detector. The fill factor essentially defines a probability that a detection will land on an active part of the detector, so because a tracklet requires two detections, a loss of 0.8^2 or 0.64 is not unexpected. Further loss against an ideal detector can be explained due to variation in image quality and detection efficiency over the Run 3 survey, but this effect has not been quantified.

SUMMARY

Early testing of the MOPS pipeline indicated that MOPS will be extremely effective in finding orbits in PS1 detection given three nights of tracklets over a month of survey data. Despite sparse data suitable for asteroid discovery in Run 3, MOPS successfully found 151 derived objects, including 10 discovery candidates, seven of which were given provisional asteroid designations by the MPC. Further analysis of the MOPS data using tracklets associated with known catalog objects demonstrates excellent astrometric performance of the PS1 system. When PS1 is able to achieve its designed surveying efficiency, we are hopeful that PS1 and MOPS will make serious inroads in detecting and cataloging asteroids hazardous to earth.

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FIGURES

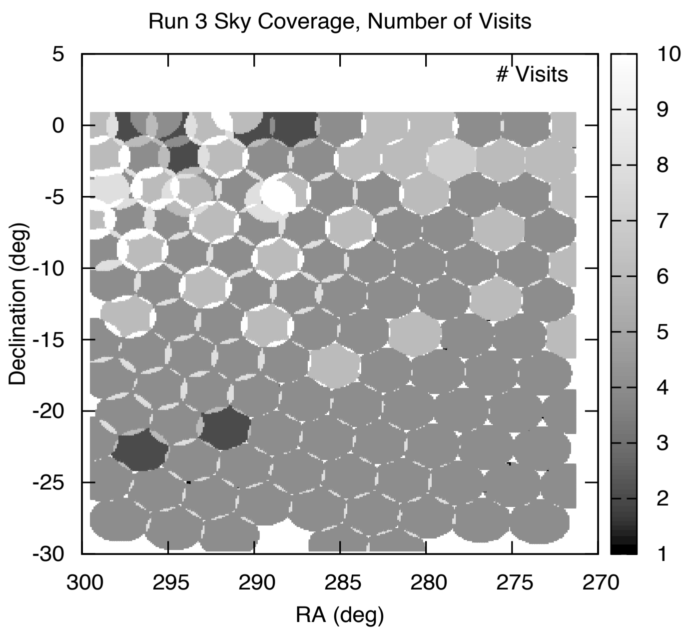

Figure 1. PS1 Run 3 sky coverage. Dark indicates fewer visits. Ecliptic latitude is between -25 and -20 degrees declination.

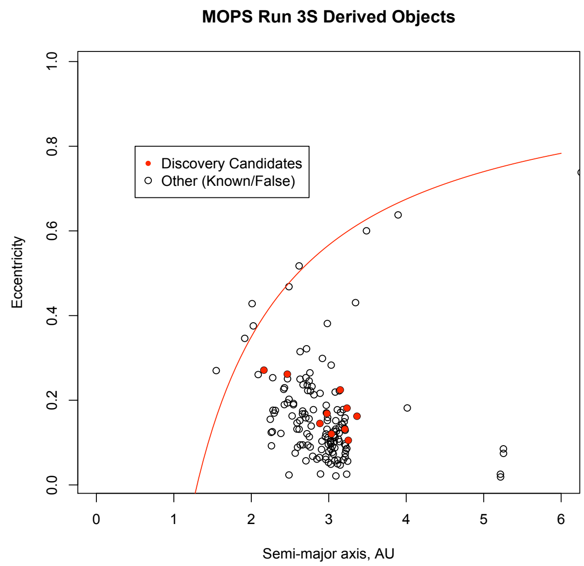

Figure 2. MOPS 3 derived objects. Red circles indicate discovery candidates.

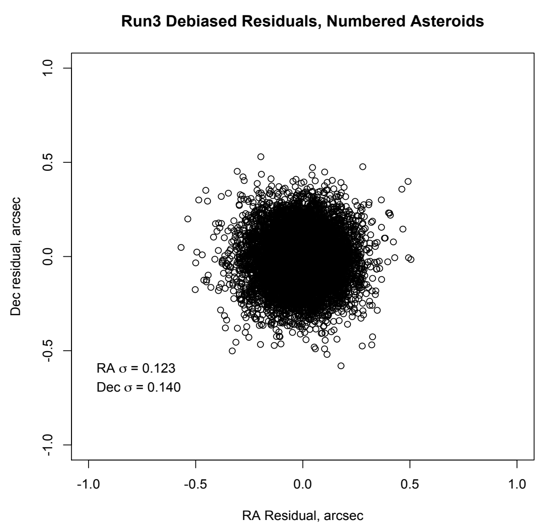

Figure 3. Debiased RA and declination residuals of Run 3 detections for improved object catalog orbits.

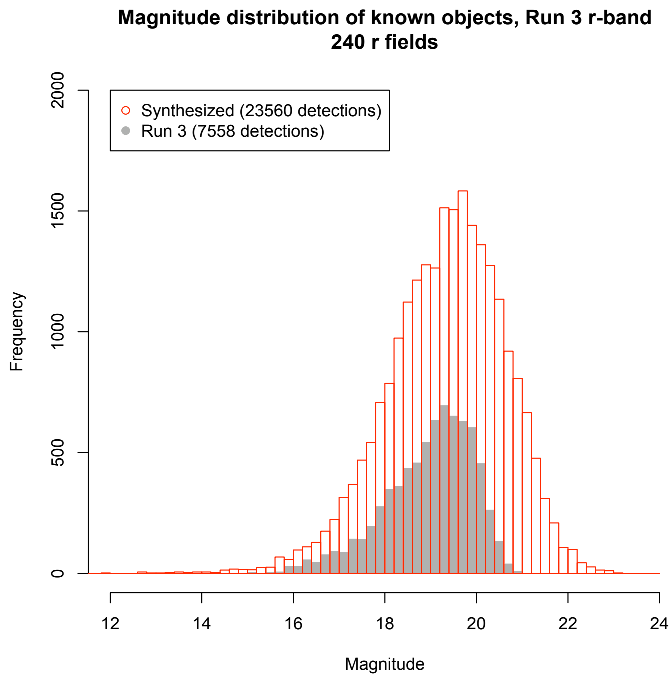

Figure 4. ***r*-band distribution of attributed tracklets (dark) vs. ideal population derived from known object catalogs.**