The Pan-STARRS Moving Object Processing System

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1. MOVING OBJECT PROCESSING SYSTEM

Pan-STARRS+MOPS (Moving Object Processing System) will be the world's 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.

Fig. 1 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-σ from the Image Processing Pipeline's (IPP) difference images [1]. This includes apparently stationary transients since they may be very distant slow moving objects, and also those trailed detections consistent with being images of fast moving objects.

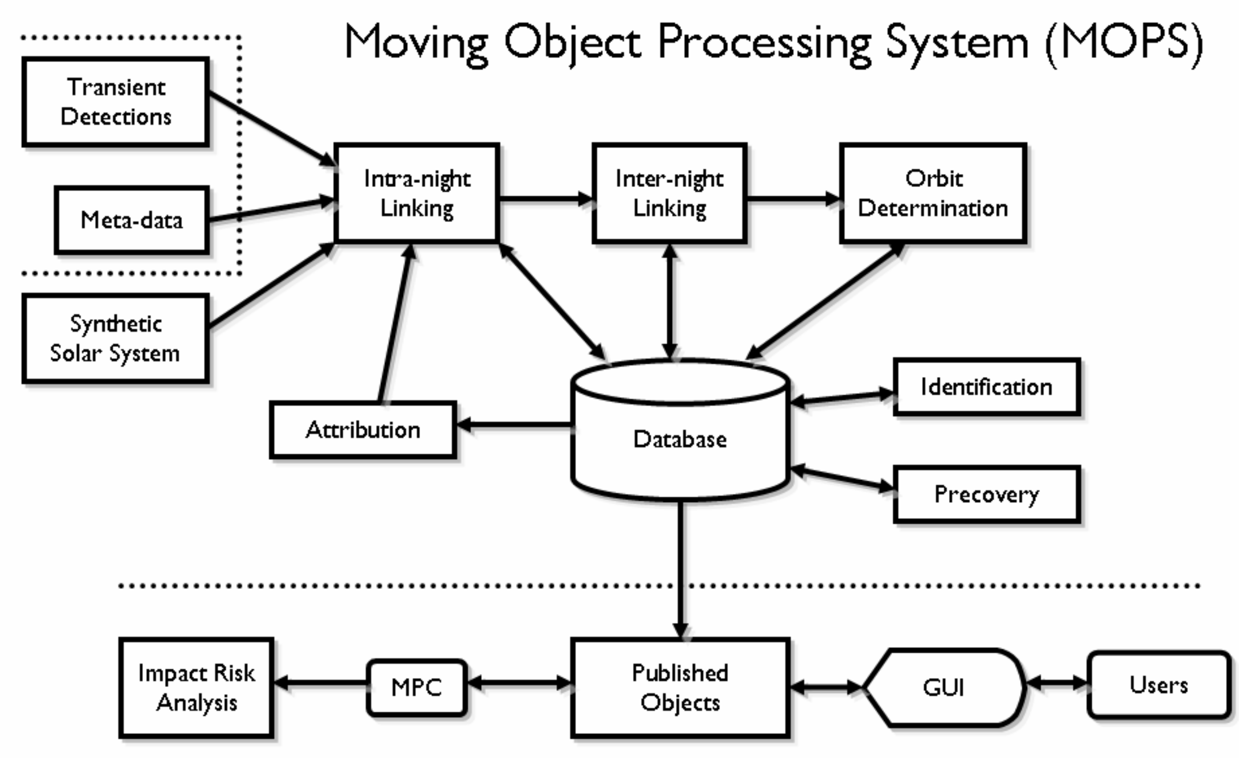

Figure 1 - Moving Object Processing System concept of operations. Data in the upper left region surrounded by dotted lines is provided by the IPP. Systems below the horizontal dotted line are not part of the MOPS.

The combinatoric problem of properly linking detections of the same object observed on a few nights over a period of a couple weeks could computationally expensive. On the ecliptic and to a limiting magnitude of r~24 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. ~2000 false 5-σ detections per field) while at 3-σ we expect about 200,000 false detections per field or a false:real ratio of about 100:1!

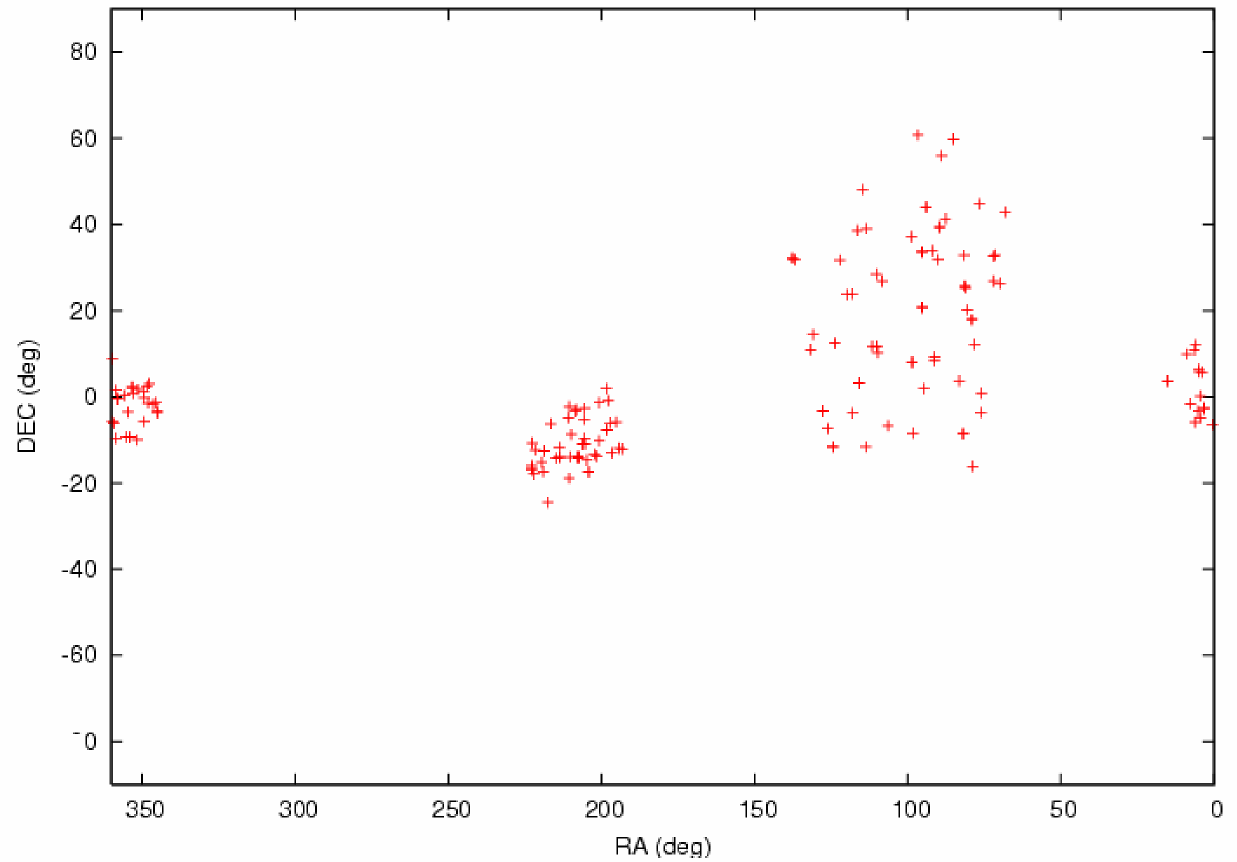

Figure 2 - NEOs with H<18 (larger than 1km diameter) detected in a single lunation by PS4. The opposition region is the large area near 100deg RA and the other areas represent the morning and evening sweet spots.

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 3-4× per lunation. We envisage a PS1 survey strategy [2] that combines a photometric & astrometric survey, a medium-deep survey and a solar system survey in an efficient manner that will allow 60% of surveying time to be utilized in a cadence suitable for linking solar system objects. An additional ~5% of surveying time will be devoted to surveying in the 'sweet-

spots' [3], the sky within about 10˚ of the ecliptic and with solar elongation from 60˚ to 90˚. Fig. 2 shows a single lunation of surveying with this survey pattern where is it clear that the sweet-spots are particularly rich in NEOs due to looking along the Earth's orbit where NEOs must pass by definition.

It is the responsibility of MOPS to identify candidate moving object 'tracklets' in the images acquired within a TTI on each night. A tracklet is composed of detections that are within an angular distance and position consistent with their elongation and orientiation with respect to one another. As shown in Table 1 our efficiency for creating tracklets [4] 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 referred to as attribution). Tracklets that can not be associated with known objects are stored for future use.

Table 2 shows the degradation in tracklet accuracy if we do not make use of the trailing information (trail length and orientation) when forming tracklets. While we can maintain a high tracklet formation efficiency, the accuracy drops by more than a factor of two and this would, in turn, require an even larger number of false inter-night linkages to be erroneously identified.

Table 1 - Standard MOPS tracklet identification performance in the opposition and sweet spot regions for the full solar system model (SSM) with full density false detections in a single lunation. Columns are: **Available** - The number of possible synthetic tracklets that could be identified with detections separated by less than one hour; **Efficiency** - the percentage of synthetic tracklets that were actually identified; **Accuracy** - the percentage of all identified tracklets that were properly identified as being synthetic; **Mixed** - the percentage of identified tracklets consisting of synthetic detections from different objects; **Bad** - the percentage of identified tracklets consisting of both synthetic and false detections; **False** - the percentage of identified tracklets consisting of false detections.

Model	Available	Efficiency	Accuracy	Mixed	Bad	False
SSM Opposition	636251	99.97%	89.2%	3.8%	3.5%	3.5%
SSM Sweet-Spots	697927	99.97%	84.7%	8.7%	4.8%	1.9%

Table 2 - As in Table 1 but for a non-standard MOPS implementation that ignores trailing information (orientation and length) for each detection. i.e. each detection as treated as a simple point.

Model	Available	Efficiency	Accuracy	Mixed	Bad	False
SSM Opposition	636251	99.91%	30.7%	14.9%	27.8%	26.6%
SSM Sweet-Spots	698110	99.96%	26.4%	26.9%	34.0%	12.6%

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 [4]. 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 as shown in Table 3 and Table 4.

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 χ^2 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 >95% of real tracks produce usable IODs and a large fraction of those produce usable ODs.

We have usable prototype code in place for moving object attribution and also precovery detection identification but have not yet examined and 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.

Table 3 - Track formation efficiency for the full solar system model with realistic astrometric error and false detections. The object types are organized in terms of heliocentric distance with Near Earth Objects (NEO), Main Belt (MB), Trojan (TRO), Centaurs (CEN), Trans-Neptunian Objects, Scattered Disk Objects (SDO) and Comets (COM).

Object Type	Available	Linked	Efficiency
NEO	350	340	97.1%
MB	151084	148526	98.3%
TRO	4161	4148	99.7%
CEN	99	99	100.0%
TRO	695	693	99.7%
TNO	275	274	99.6%
COM	29	29	100.0%
Total	156693	154109	98.4%

Table 4 -MOPS track identification performance for different solar system models (SSM). The SSM is the full density model and SSM/250 is every 250th object. The MB/N models have full densities of all SSM components except for the MB which includes only every N th object. Each model contains false detections at the full density level. Columns are: **Objects** - the number of different synthetic solar system objects included in the simulation; **Density** - density of objects in the model compared to the full model; **Available** - the number of synthetic tracks generated in the simulation; **Linked** - the number of synthetic tracks that were properly linked; **Efficiency** - the fraction of generated tracks that were correctly linked; **Tracks** - the total number of tracks found in the simulation; **Accuracy** - the percentage of identified tracks that represent synthetic tracks.

Model	Objects	Density	Available	Linked	Efficiency	Tracks	Accuracy
SSM/250	43445	0.4%	680	679	99.9%	94041	0.7%
MB/100	960758	8.8%	7658	7644	99.8%	138646	5.5%
MB/10	1860758	17.1%	21828	21766	99.7%	295529	7.4%
SSM	10860758	100.0%	156693	154109	98.4%	44814287	0.3%

2. PS1, MOPS AND THE EARTH IMPACT RISK

The prototype Pan-STARRS telescope on Haleakala will provide the best measurement of the NEO population 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 NEO's orbit and size distribution (especially at small sizes) thereby allowing a much better characterization of the Earth impact risk.

Collapsing the error bars on the size and orbit distribution is also important because it allows a better tuning of the survey characteristics of 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 [5,6] would suggest. PS1 will resolve these issues.

3. SUMMARY

The PS1 and Moving Object Processing System (MOPS) will be the world's 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 world's first comprehensive model of the solar system including over 10^7 objects that might be discovered by PS4 during the course of its ten year operational lifetime. The MOPS is the first asteroid and comet linking system in the world 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.

4. REFERENCES

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