

## Asteroid Models from the Pan-STARRS Photometry

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**Abstract.** We present simulations on the asteroid photometric data that will be provided by the Pan-STARRS (Panoramic Survey Telescope and Rapid Response System). The simulations were performed using realistic shape and light-scattering models, random orientation of spin axes, and rotation periods in the range 2–24 h. We show that physical models of asteroids can be reconstructed from this data with some limitations (possible multiple pole solutions). We emphasize the potential of sparse photometric data to produce models of a large number of asteroids within the next decade and we outline further tests with fast and slow rotators, tumblers, and binary asteroids.

**Keywords:** asteroids, photometry

### 1. Introduction

Physical asteroid models can be constructed from unprecedentedly small sets of single calibrated photometric measurements sparse in time but well distributed in observing geometries. Sidereal periods, pole directions, coarse shape estimates, and solar phase behavior can be solved with accuracy sufficient for the statistical analysis of a large sample of the asteroid population (Kaasalainen, 2004). This approach is roughly two orders of magnitude more time-efficient than the usual lightcurve photometry.

The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) is an ongoing project at the Institute for Astronomy of the University of Hawaii. It presents a novel approach to the need for a Large Synoptic Survey Telescope proposed by the National Academies of Sciences report “Astronomy and Astrophysics in the New Millennium” (2001). It is

designed to provide a deep survey of large sky areas and detect moving objects. Among many other science goals, Pan-STARRS will provide calibrated brightness measurements of all detected asteroids.

In order to explore the potential of the Pan-STARRS photometric data set, we simulated the Pan-STARRS photometric measurements and tested the lightcurve inversion results. In the following sections we present our tests and show that Pan-STARRS will provide photometric data from which the spin states and shapes of the observed asteroids can be derived.

## 2. Pan-STARRS Design and Observation Schedule

Pan-STARRS uses four 1.8 m telescopes, each with a  $\sim 7$  deg<sup>2</sup> field-of-view CCD mosaic camera with 1.44 billion pixels in the focal plane. This results in a spatial sampling of  $\sim 0.3$  arcseconds per pixel, which makes the telescope and camera well suited for all-sky survey of moving objects. The four telescopes will simultaneously observe the same part of the sky, allowing the images to be stacked to reach a limiting magnitude of  $R \sim 24.5$ . The Pan-STARRS project spans a full range of science goals, from planetary to cosmological, and promises to present a new paradigm in observational astronomy. It will perform a survey of the Solar System that far exceeds any previous surveys, going more than 10 times fainter than any existing full sky survey (LINEAR or LONEOS) and with a much higher return-rate for each part of the sky. See Hodapp et al. (2004) for more details on the design of Pan-STARRS and Milani et al. (2006) for the Pan-STARRS surveying and solar system model overview.

The construction phase is fully funded and under way with the construction of the PS1 prototype on Haleakela, Hawaii. PS1 is a single 1.8 m telescope with a full 7 sq. degrees field-of-view camera. Starting in early 2007, PS1 is scheduled to start its Solar System Survey (S<sup>3</sup>) designed to find objects ranging from the close in near-Earth objects to the distant trans-Neptunian population. The S<sup>3</sup> is being designed to cover almost 6000 sq. degrees each lunation and thus provides a significant leap in surveying of the Solar System by essentially providing an all sky survey to a limiting magnitude of  $R \sim 23.5$ . The photometric accuracy is expected to be 3% for  $V \sim 21.8$  mag, corresponding to an absolute magnitude of  $H \sim 17$  mag for main belt asteroids. We expect that after 10 years of Pan-STARRS surveying we will be able to determine poles, periods and shapes for about  $10^5$  asteroids.

S<sup>3</sup> will image a total of  $\sim 1100$  deg<sup>2</sup> in the morning and evening sweet spots (sky regions near-quadrature with  $|\beta| < 10^\circ$  and  $-90^\circ < l < -60^\circ$  or  $+60^\circ < l < +90^\circ$ , where  $l$  is the solar elongation and  $\beta$  is the ecliptic latitude), as well as a  $\sim 4600$  deg<sup>2</sup> opposition region ( $|l| > 150^\circ$  and  $|\beta| < 40^\circ$ ). S<sup>3</sup> is designed to be performed such that most bright objects in the survey will be observed on three

separate nights over an 8–12 day arc. Each field is observed twice each night separated by ~15 min. This means that most objects detected during a lunation will have 6 observations over the three nights. If an object is bright enough, it will typically be observed in 2 or 3 lunations when at opposition and once in each of the morning and evening sweet spots. The S<sup>3</sup> survey will be performed in a wide Solar System bandpass filter designed to be optimal for the detection of asteroids. It is expected that serendipitous detections of a significant number of solar system objects will occur in other Pan-STARRS surveying modes.

A typical time sequence of observations for a main belt asteroid is shown in Figure 1. Two groups of data points can be recognized in the plots: Observations around opposition at phase angles <15° and observations at larger phase angles corresponding to the evening and morning sweet spots. The large brightness variations on the left plot are caused by the changing distance between the asteroid, the Earth and the Sun. On the right plot, the brightness is reduced to 1 AU distances from the Earth and the Sun and the remaining variations are due to asteroid’s rotation. The data were generated using Hapke’s scattering model.

### 3. Simulations and Lightcurve Inversion Tests

One of the key features of the Pan-STARRS Moving Object Processing System (MOPS) is that the survey will be fully simulated to develop and test the observing strategy and pipeline system before any real data is available. To achieve this we have created a model of the entire Solar System containing ~10 million objects and used a commercial observatory scheduling package, TAO (Tools for Automated Observing, Paulo Holvorcem), to devise a survey

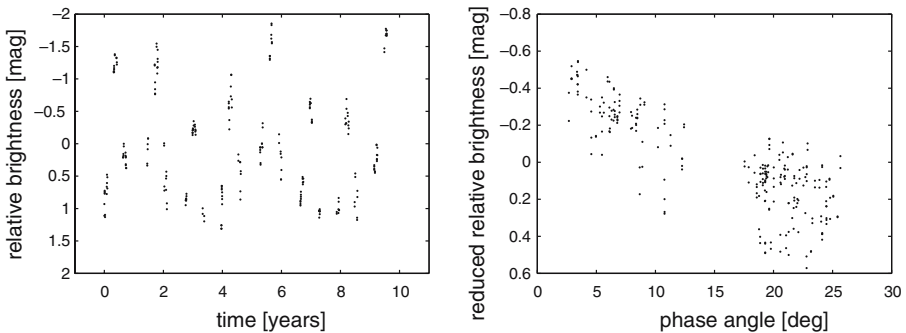


Figure 1. (Left) A typical time sequence of observations of a main belt asteroid during 10 years of observation (brightness is not reduced to unit distances from the Earth and the Sun) and (right) the corresponding coverage of phase angles (brightness is reduced to unit distances).

pattern consistent with the description above for the expected 10 years of Pan-STARRS operations. This allows us to create a simulated survey which, together with estimated astrometric and photometric errors and false detections, allows for testing and preparation of the MOPS pipeline. The Pan-STARRS Solar System Survey Simulation ( $S^4$ ) used in this work takes every 250th object of each population in our Solar System Model and provides a full 10-year simulated survey for these objects. This allows us to explore the full 10-year cadence for  $\sim 40,000$  objects.

For our lightcurve inversion simulations we selected a few objects from each of three asteroid populations (near-Earth asteroids, NEAs; main belt asteroids, MBAs; and trans-Neptunian objects, TNOs) from the sub-sample of objects with hundreds of detections in the project's 10-year time span. A few percent of objects were detected hundreds of times – but a few percent of the expected  $10^7$  total number of objects is still an impressive sample. For the selected objects, a Pan-STARRS “lightcurve” consists of  $\sim 150$ – $300$  individual points spread over the 10-year observation interval. We used different shape models, pole directions, rotation periods, and noise level to test the Pan-STARRS data's potential for reconstructing asteroid physical models.

We performed our tests using the lightcurve inversion technique developed by Kaasalainen et al. (2001) and we processed the sparse time sequences in the same way as Kaasalainen (2004): The rotation period is searched by scanning the expected period range (2–24 h in our tests) with a few initial poles. For the period yielding the lowest rms fit residual, the best pole and shape solution is found using a dense initial pole grid. We used radar shape models<sup>1</sup> of asteroids (6489) Golevka and (2063) Bacchus (see Figure 4) and Hapke's scattering model for the simulated data. In the inversion process, we used the empirical light-scattering model of Kaasalainen et al. (2001). Its three-parameter linear-exponential phase function fits Hapke's model and real data well as shown by Kaasalainen et al. (2003) or Kaasalainen et al. (2004).

### 3.1. PHOTOMETRIC CALIBRATION ERRORS

In order to identify limits on the maximum acceptable noise level for the sparse photometric data, we ran tests with three different Gaussian noise levels: 3, 5, and 7%. The best model always fit the data down to the noise level for the correct period. If the brightness measurements are too noisy, there is no unique period solution – the correct period is lost among many

<sup>1</sup> 3D asteroid model courtesy of Scott Hudson, Washington State University, <http://www.tricity.wsu.edu/~hudson/Research/Asteroids/index.htm>

other possible periods. Typical results are shown in Figure 2 – we used the Golevka shape model, pole direction ( $\lambda = 65^\circ$ ,  $\beta = 10^\circ$ ) in the ecliptic coordinates and a rotation period of 5 h. The correct period (indicated with the dotted vertical line) is always found. However, for higher noise levels, there are other periods that fit the data equally well. Note that there remain false period solutions for the TNO simulation even for 3% noise. Those false periods correspond to higher and lower harmonics of the correct period and it is a common characteristic of many of our TNO tests. This is caused by the fact that the viewing/illumination geometry of a TNO changes very little during 10 years. The false periods are usually 1/2 and 3/2 of the correct value. However, these false periods can be rejected if we assume principal axis rotation and a lightcurve with two maxima and minima per revolution. The half period usually leads to a shape with its spin axis not corresponding with the principal axis, and the 3/2 period gives a shape with a typical triangular pole-on silhouette.

The expected photometric calibration errors of Pan-STARRS should not exceed the 3% level for asteroids brighter than  $\sim 21.8$  mag in the *R* filter – fully

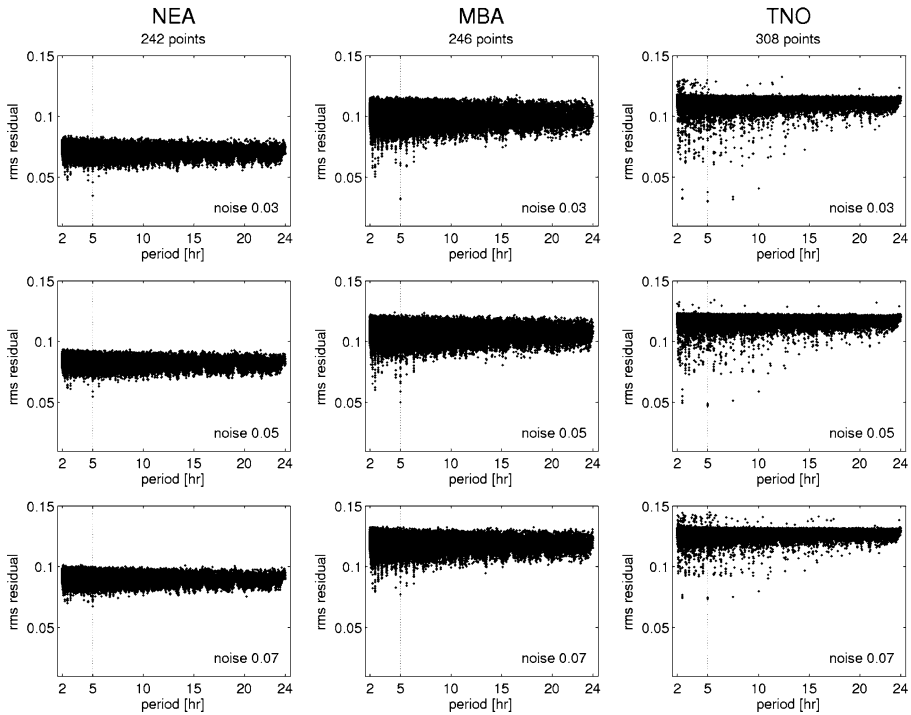
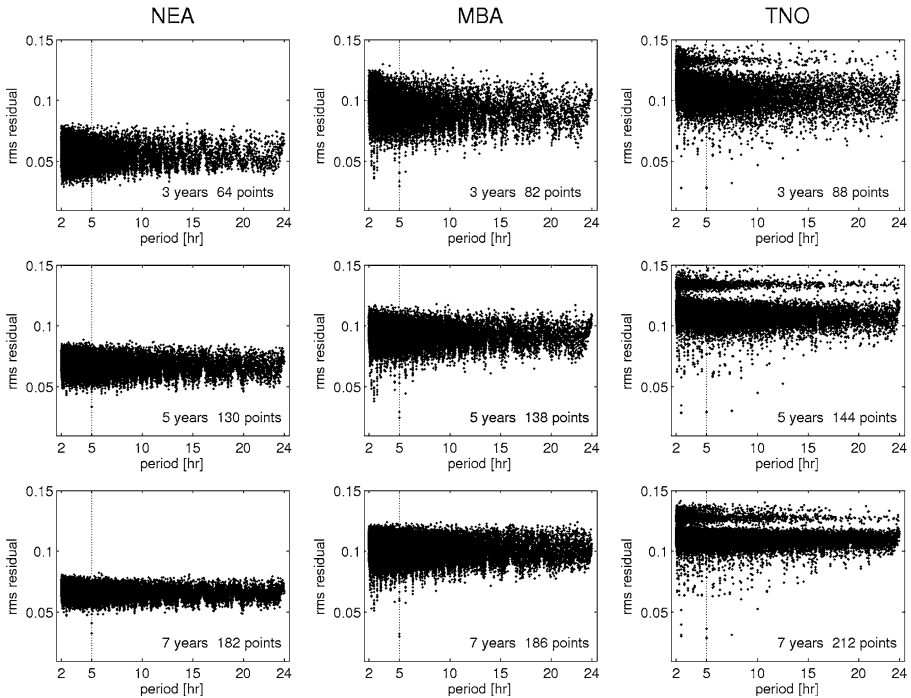


Figure 2. Period search results for three asteroids and different noise levels. The testing data was simulated with the Golevka shape model, a rotation period of 5 h (the dotted vertical line), and full 10-year cadences. The number of data points of each tested time-sequence is indicated in the first three plots.

sufficient for the lightcurve inversion. This is also lower than the photometric modelling error due to the scattering law. The noise can be higher for more elongated shapes – such asteroids have higher lightcurve amplitudes and the correct period stands out clearly even with more noisy data.

### 3.2. OBSERVATION INTERVALS

We also performed the same period search tests with reduced data set in order to determine when the first lightcurve inversion results from Pan-STARRS can be expected. We used only the first 3, 5, and 7 years from the 10-year cadences. Results for three asteroids are shown in Figure 3. The conclusion for NEAs and MBAs (drawn from the full suite of tests, not only from the results presented in Figure 3) is that unique period detection (with the 3% noise) is possible after about 5 years of observation. There are always false period solutions for observations covering only 3 years or less. For a TNO, there are often harmonic period solutions even when using the whole 10-year data set. The correct period model always fits the data down to the



*Figure 3.* Period search results for three asteroids and different intervals of observation. The testing data was simulated with the Golevka shape model, the rotation period of 5 h (the dotted vertical line) and 3% noise.

noise level but there are also other possible periods with the same rms residual when less data points (a short observation interval) are available. As the number of detections and the time baseline increases, the average rms residual level increases and the correct period stands out clearly.

### 3.3. POLE AND SHAPE SOLUTIONS

The best pole solutions were very close (within a few degrees) to the original directions in all our tests with the NEA and MBA 10-year cadences and 3% noise level. In many cases, the pole direction cannot be derived uniquely – there are one or more poles giving nearly the same fit residual. In some cases, the false pole solutions can be recognized due to their non-physical rotation state – their spin axes differ from the principal axes. Some orbit and cadence configurations seem to give more pole solutions than others, and we will run more simulations to identify the typical situation. Pole directions of TNOs cannot be derived from the Pan-STARRS data since the observation geometry changes very little during 10 years of observation.

Figure 4 gives an example of asteroid shape reconstruction. We used radar models of asteroids Golevka (nonconvex irregular shape) and Bacchus (elongated ellipsoid-like shape), a MBA orbit, and a rotation period of 5 h. Note the  $\lambda+180^\circ$  ambiguity in the pole direction. This is an inevitable ambiguity in all disk-unresolved observations for targets orbiting near the plane of ecliptic (Kaasalainen and Lamberg, 2006).

## 4. Conclusions

The Pan-STARRS photometric data will be fully capable of providing physical models of near-Earth and main-belt asteroids. About 100 calibrated data points within 4–5 years suffice for such models for which the calibration errors should not be higher than  $\sim 3\%$ . For TNOs, the data is sufficient for rotation period determination. In the next decade, GAIA photometry will provide another dataset for thousands of asteroids and it will be possible to process both Pan-STARRS and GAIA data simultaneously. With GAIA, we can also use the astrometric photocentre offset effect simultaneously with photometry to improve the models (Kaasalainen et al., 2005).

A large database of thousands of asteroid spin states and basic shapes provides us the ability to understand key issues related to the formation and evolution of both near-Earth and main-belt asteroids. Such a database can be constructed without having to obtain traditional lightcurves that require a dense time series of photometric measurements. From this database we can then select interesting targets (peculiar shapes, probable binary systems, etc.)

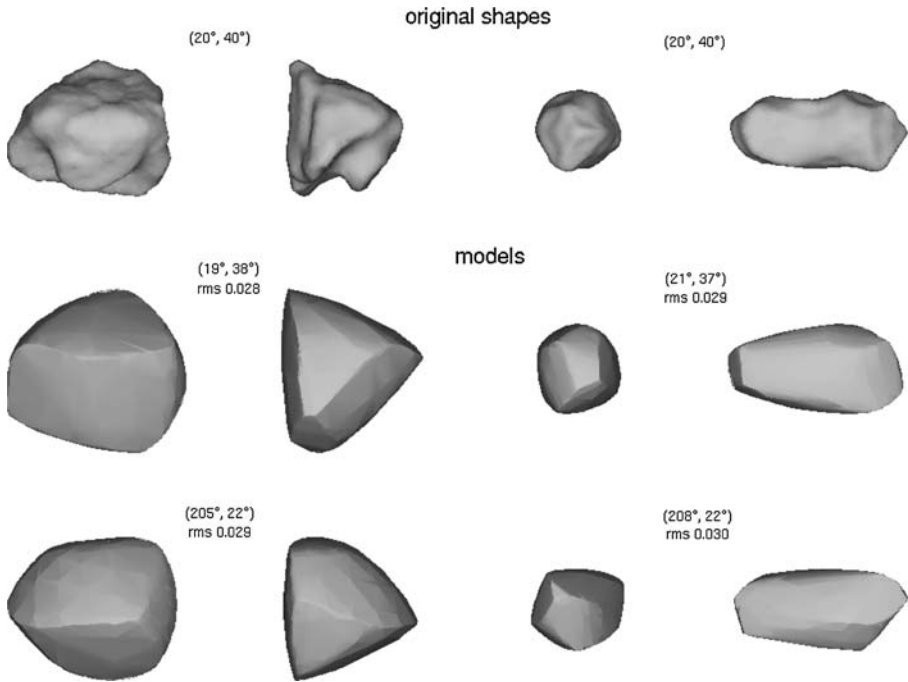


Figure 4. Original shapes (top) and derived shape models. The testing data was simulated for a MBA orbit with the Golevka (left) and Bacchus (right) radar shape model, pole direction  $(20^\circ, 40^\circ)$ , and 3% noise. There are two edge-on views for each model that are  $90^\circ$  apart. Together with the correct solution (the second row), there is a rival solution (the third row) that differs by  $\sim 180^\circ$  in the ecliptic longitude  $\lambda$  of the pole direction.

that require followup observations such as full lightcurves or radar experiments. In this manner we will improve the efficiency of telescope time devoted to detailed observations.

#### 4.1. FUTURE WORK

So far, we have simulated only asteroids rotating in the principal axis mode with periods in the range 2–24 h. This is only the beginning of a more extensive study on the use of Pan-STARRS data. We will continue by testing Pan-STARRS time-sequence series for fast and slow rotating asteroids, tumbling asteroids, and binary objects. Preliminary tests show that: (i) none of these cases can be misinterpreted as a principal axis rotator with a 2–24 h period, (ii) the correct periods can be derived even for fast rotating ( $\sim 0.2$  h) objects, (iii) there are false period solutions of one half or double of the correct value for longer periods ( $\sim 100$  h), and (iv) some binary targets (with large enough secondary/primary size ratio and suitable geometry of the orbit)

can be detected through brightness drops during mutual events as exposed in brightness versus phase angle figures.

During the first year of Pan-STARRS observation we will compare the measured photometric data with predictions based on available asteroid models (see Kaasalainen et al., 2004 and references therein). This will enable us to derive the real calibration errors, frequency of outliers, systematic errors, etc.

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