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# A Pan-STARRS Search for Distant Planets

**Matthew Holman** (1), Matthew Payne (1) and the Pan-STARRS-1 Team (2)
(1) Center for Astrophysics| Harvard & Smithsonian, Cambridge, Massachusetts, USA (2) (mholman@cfa.harvard.edu)

## Abstract

Several lines of evidence, both theoretical and observational, indicate that additional planets in the outer solar system remain to be discovered [9, 5, 17, 2]. We recently developed a novel technique to search for solar system bodies [13]. Here we apply that method to a search for distant planets and minor planets in Pan-STARRS data. In addition to the results of that search, we present a characterization of the detection limits and biases of our search using our newly-developed Pan-STARRS survey simulator.

## 1. Pan-STARRS

Recent dynamical and observational investigations have rekindled enthusiasm for the possibility of additional planets, orbiting undetected in the far-reaches of the outer Solar System [9, 5, 17, 2, 6, 3]. A number of searches are underway [11, 3]. We have used data from the Pan-STARRS-1 telescope to carry out a search for such a distant, massive body.

The $1.8m$ Pan-STARRS-1 telescope located on Haleakala, Maui, has a 1.4 Gigapixel camera with a 7 $deg^2$ FoV which images the entire visible sky dozens of times per year, with the aim of identifying astrophysical transients and moving objects in the Solar System [7]. The current NEO survey is carried out in "quads" (four observations per night, spread over an hour). During dark time, these are in the *w*-band, and during bright time, these are in the *i*-band. These quad observations, designed for NEO detection, are also suitable for the detection of trans-Neptunian objects (TNOs) [8, 14, 12].

## 2. Search

The input to our search are the source catalogs from the direct, undifferenced Pan-STARRS-1 exposures. We eliminate any detections that coincide with the location of a known, stationary source (star or galaxy) in a deeper catalog developed from the image stacks [15]. In addition, we employ a variety of techniques to eliminate spurious detections.

From the catalogs of remaining sources, we search for tracklets and link tracklets using the HelioLinC method [13]. This method is particularly well-suited to very slow-moving objects, even those for which the motion within a night might be too small to detect.

## 3. Characterization

Perhaps even more important than the search itself is a detailed, quantitative analysis of the survey's detection limits and biases. This information is essential for the rigorous interpretation of these survey results. Such simulators have been developed for CFEPS/OSSOS [1], NEOWISE [16], and other surveys, leading to detailed results on the small body populations throughout the solar system. We have developed a high-fidelity survey simulator for Pan-STARRS. This simulator takes positions, magnitudes, and rates of motion calculated from a solar system model [10] at the times and locations of individual Pan-STARRS exposures. It then inserts synthetic detections into the resulting exposure source catalogs, accounting for the details of the camera (including the pixel mask), photometric zero point, sky conditions, and all other essential details. The source catalogs, including synthetic detections, are then run through our full search pipeline. This approach allows a clear, quantitative statement about the prevalence of distant planets, as seen by Pan-STARRS.

## 4. Summary

We present the results of a search for distant planets in our solar system using data from the Pan-STARRS survey. We employ a novel, efficient search technique. In addition, we enhance the value of our search by completing a detailed characterization of its efficiency and biases.

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