Development of an observational error model, and astrometric masses of 28 asteroids

Thesis submitted by
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Statement on the Contribution of Others

This dissertation produced three published papers:

- Chesley, S.R., Baer, J.J., Monet, D.G. Treatment of Star Catalog Biases in Asteroid Astrometric Observations, 2010, Icarus 210, 158. Sections 1-5 of this paper correspond to section 4 of the dissertation. Steve Chesley coordinated the community-wide effort to resolve the star catalog biases, and was therefore the lead author of this paper. I wrote sections 1, 2, 4.1, 5, 7.1, and 8 of this paper, while Steve wrote sections 3, 4.2, 6, and 7.2. For the purposes of this dissertation, I have rewritten all of the text that Steve contributed in my own words. Dave Monet contributed the catalog-specific bias look-up table described in that paper's section 4.2. With the exception of sections 6 and 7 (which are not included in this dissertation), I performed all of the calculations for this paper.

- Baer, J.J., Chesley, S.R., Milani, A. Development of an observational error model, 2011, Icarus 212, 438. The content from this paper corresponds to sections 3 and 5 of the dissertation. I wrote all of this paper, and performed all of the research associated with it.

- Baer, J.J., Chesley, S.R., Matson, R.D. Astrometric Masses of 26 Asteroids and Observations on Asteroid Porosity, 2011, Astronomical Journal, 141, 143. The content from this paper corresponds to sections 2, 6.0, 6.3, and 7.0 of the dissertation. I wrote all of this paper. Rob Matson contributed precovery observations of several asteroids; but I performed all of the calculations and analysis.

Intellectual support was provided by the following collaborators:

- Steve Chesley (Solar System Dynamics Group, Jet Propulsion Laboratory) acted as my Principal Supervisor. We discussed all aspects of this effort, including the design, construction, implementation, and validation of the observational error model, and the interpretation of the asteroid mass determinations. Steve coordinated the community-wide effort to resolve the star catalog biases, and was therefore the lead author of the first paper; however, for the purposes of this dissertation, I have rewritten all of the text that Steve contributed to that paper in my own words. Steve was also co-author on the second and third papers.

- Andrea Milani (Department of Mathematics, University of Pisa) helped conceive the idea of an observational error model, and provided guidance throughout its development. He was a co-author on the second paper.

- Rob Matson (Science Applications International Corporation) was a co-author on the third paper, contributing precovery images and reduced positions of several test asteroids.

- Dave Monet (U.S. Naval Observatory) was a co-author on the first paper, contributing the catalog-specific bias look-up table.

- Dan Britt (Department of Physics, University of Central Florida) shared his expertise on asteroid mineralogy, and discussed the appropriate grain densities for different asteroid classes.

- Alan Harris (Space Science Institute) helped locate a reliable occultation-based diameter for asteroid 8 Flora.

The full text of this dissertation was written by me; and all calculations (unless otherwise noted) were performed by me.

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Abstract

As a large asteroid encounters a smaller body, its gravitational attraction perturbs the trajectory of the smaller asteroid. The method of astrometric mass determination uses a least-square algorithm to simultaneously solve for both the orbit of the small asteroid, and the mass of the larger asteroid required to produce the observed perturbation. Since the perturbations are quite small, the observations of the smaller asteroid must be highly precise; and the perturbations of other asteroids must be accounted for.

Current practice, however, is to assume that all observations of a given era have the same uncertainty, and that the errors in these observations are uncorrelated. These assumptions are unrealistic; and they lead to sub-optimal masses and orbits. We therefore pursue development of an observational error model that provides realistic estimates of the uncertainties and correlations in asteroid observations.

In the course of our first attempt to construct the error model, we detected a significant bias in the observations of numbered asteroids, due to position-dependent errors in the star catalogs from which the observations were reduced. Before proceeding further, we developed a method to remove these biases, and undertook extensive calculations to validate its performance. Implementing this technique, we completed development of the error model, and demonstrated that it produces orbits that are both more accurate, and more precise.

We then used the new error model to iteratively refine an integrated ephemeris of 300 large asteroids, which allowed us to deduce the masses of 28 main-belt asteroids. These include the first published masses of 5 Astraea ($1.255 \pm 0.003 \times 10^{-12} M\odot$) and 39 Laetitia ($2.83 \pm 0.73 \times 10^{-12} M\odot$).

After combining our mass estimates with those of other authors, we studied the bulk porosities of over 50 main-belt asteroids; and after reviewing the collisional evolution of main-belt asteroids, we concluded that asteroids as large as 300 km in diameter may be loose gravitational aggregates. This finding will place a specific constraint on models of main-belt collisional evolution. Additionally, we found that C-type asteroids tend to have significantly higher macroporosity than S-type asteroids; and after reviewing thermal models of asteroid accretion, we concluded that distant C-type asteroids likely have a cometary-type structure and composition that results from a lack of global heating following their initial accretion.

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