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Treatment of star catalog biases in asteroid astrometric observations

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ABSTRACT

In this paper, we discuss the detection of systematic biases in star positions of the USNO A1.0, A2.0, and B1.0 catalogs, as deduced from the residuals of numbered asteroid observations. We present a technique for the removal of these biases, and validate this technique by illustrating the resulting improvements in numbered asteroid residuals, and by establishing that debiased orbits predict omitted observations more accurately than do orbits derived from non-debiased observations. We also illustrate the benefits of debiasing to high-precision astrometric applications such as asteroid mass determination and collision analysis, including a refined prediction of the impact probability of 99942 Apophis. Specifically, we find the IP of Apophis to be lowered by nearly an order of magnitude to 4.5×10^{-6} for the 2036 close approach.

1. Introduction

While future asteroid surveys, such as PanSTARRS, promise to routinely provide observations with uncertainties on the order of 0.1 arcsec (Jedicke et al., 2004), many high-precision astrometric applications, such as mass determination and Yarkovsky analysis, study interactions fixed in the past, or rely upon long observational baselines to model slowly evolving phenomena. So while new observations may be helpful, we must also use contemporaneous and historical observations. Our long-term goal, therefore, is to create a statistical error model of asteroid observations, providing realistic, observatory-specific estimates of error correlations and uncertainties that will allow us to make the best possible use of the existing body of observations.

The astrometric reduction of such observations relies heavily on accurate star catalogs; background stars in an image are identified, and used as references against which the positions of the head and tail of an asteroid trail may be determined. Ideally, star catalogs should be "dense and deep", containing a great many stars of varying brightness distributed throughout the entire sky, allowing high-precision astrometry regardless of asteroid size or location.

In that context, three all-sky US Naval Observatory star catalogs are among the most useful. The USNO A1.0 catalog, introduced in 1996, contains 488,006,860 sources down to V magnitude 20, with an estimated accuracy of 0.25 arcsec (Monet et al., 1998). The A2.0 catalog, introduced in 1998, is an update of A1.0 that moves the reference frame from the Guide Star Catalog to the ICRF; it contains 526,280,881 sources (Monet, 1998). The B1.0 catalog, introduced in 2003, contains 1,042,618,261 objects down to V magnitude 21, with an estimated accuracy of 0.20 arcsec (Monet et al., 2003).

Note that other catalogs, such as UCAC2 and 2MASS, have smaller estimated position errors; but these catalogs each have limitations relative to B1.0. The UCAC2 catalog, introduced in 2004, contains 48,330,571 stars with positions accurate to within 0.07 arcsec at the limiting magnitude of 16; but it only covers the sky from declination $-90°$ to $+40°$ (Zacharias et al., 2004). (Note: The recently introduced UCAC3 catalog (Zacharias et al., 2004) covers the entire sky, thus resolving this limitation.) The all-sky 2MASS catalog, introduced in 2003, contains 470,992,970 objects, with positions accurate to within 0.07 arcsec (Skrutskie et al., 2006); but it is limited to V magnitude 17, meaning that reference stars may be overexposed in images of small asteroids.

While creating the first iteration of a statistical error model of asteroid observations, we detected significant biases in the residuals of the numbered asteroids, which were traced to biases in the star catalogs from which those observations were reduced.

After describing our discovery and investigation of these biases (Section 2), we will describe the available asteroid astrometric data (Section 3). Next, we present a technique to debias these observations (Section 4), and demonstrate that it substantially eliminates systematic errors in orbit fits of the numbered asteroids (Section 5). We validate this new debiasing technique by demonstrating that it produces orbits that predict better, which is the crucial test of the quality of an orbit estimate (Section 6). Finally, we illustrate the application of catalog debiasing to issues such as estimating the mass of perturbing asteroids, and assessing the probability of an impact for potentially hazardous asteroids (Section 7).

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With the catalog biases resolved, a future paper will describe the subsequent development of a statistical error model for asteroid observations, demonstrate its validity, and detail its applications.

2. Evidence for bias

Star catalog biases were encountered during the development of a statistical error model for astrometric asteroid observations, as described in Carpino et al. (2003). Such a model requires that the observational residuals be unbiased, normally distributed, and uncorrelated.

In testing the first iteration of our error model, however, it became clear that these assumptions were being violated.

As illustrated in Fig. 1, for instance, probability distributions of the nominal declination residuals for the numbered asteroids revealed a clear bias of approximately +0.16 arcsec. Significantly, no such bias is evident in the right ascension residuals; this led us initially to believe that only the declination observations were affected.

Additionally, we calculated a kurtosis of approximately 4.6 for both the RA and the DEC residual probability distributions depicted in Fig. 1; this compares to a kurtosis of 3.0 for the standard normal distribution, indicating that the RA and DEC distributions are slightly peaked, thus deviating somewhat from the expected normal distribution. Adjusting the chi-square observation rejection threshold in the orbit determination algorithm failed to reduce either kurtosis to expected levels. (Note: The definition of kurtosis used in this paper results in a normal distribution having a kurtosis of 3.0.)

Finally, as will be discussed in Section 5.3, the residuals from closely-spaced observations of the same asteroid made by the same observatory appeared highly-correlated. While the correlations associated with each specific observatory differed somewhat in magnitude, they remained significant even for observations separated by several days.

Based on these data, we hypothesized that there were systematic declination biases in the star catalogs used to reduce the asteroid observations. And as we investigated further, we encountered evidence outside of our own work.

Fig. 2, dating to mid-2008, depicts histograms of the postfit means of right ascension and declination residuals for the 1649 numbered asteroids under automated orbit maintenance at that time. While the right ascension histogram shows a symmetric distribution with a mean of 0.004 arcsec and a standard deviation of 0.057 arcsec, the declination histogram is decidedly nonGaussian and asymmetric, with a mean of 0.074 arcsec and a standard deviation of 0.095 arcsec.

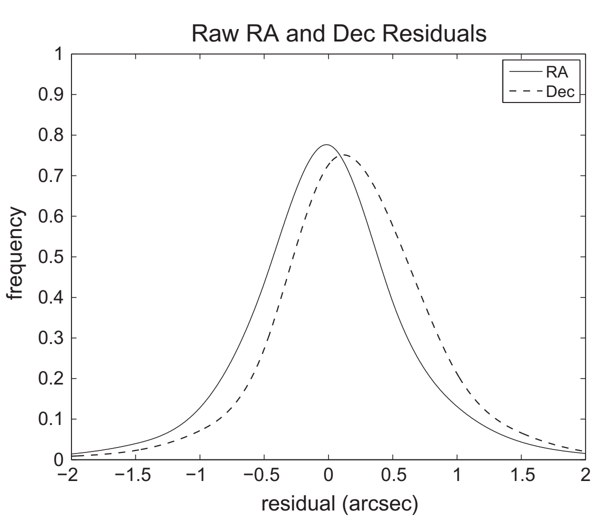

Fig. 1. Nominal residuals of the numbered asteroids, illustrating DEC bias.

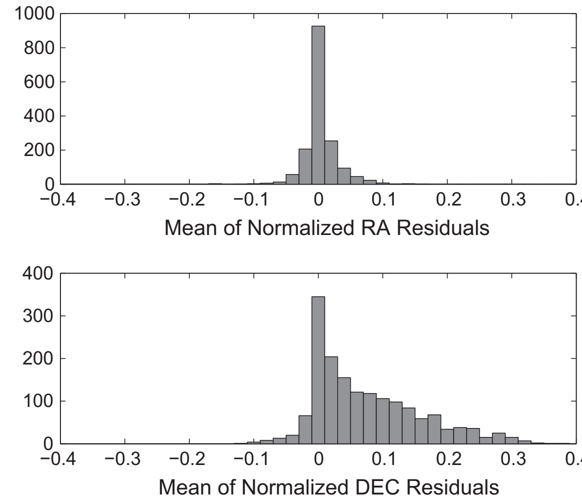

Fig. 2. Mean of normalized postfit residuals for 1649 numbered asteroids under automated orbit maintenance as of mid-2008, including all numbered NEAs, plus a handful of other targets of interest, such as space mission targets. The residuals were normalized by dividing each residual by its corresponding weight; and since the vast majority of observations are weighted at 1 arcsec, the abscissa is approximately in arcsec.

Upon analysis of the Rosetta spacecraft's encounter with Asteroid 2867 Steins, Morley (T. Morley, private communication) independently deduced a bias of +0.212 arcsec in the declination observations of that asteroid. However, to fully account for the observed encounter geometry, a right ascension bias of +0.092 arcsec was also necessary. This was the first indication that a bias was present in both coordinates. As Morley noted, a systematic bias in the right ascension observations of asteroids would not be immediately obvious, since a least-squares orbit determination algorithm would simply rotate the calculated orbit in the equatorial frame about the celestial pole to minimize the RMS error, thus eliminating the evidence of a net right ascension bias. Since none of the other orbital parameters could be manipulated so as to eliminate the declination bias, it appeared to be the only systematic error in the observations.

As will be described more fully in Section 7.2.1, Mauna Kea Observatory (MPC observatory code 568) independently noted a persistent positive declination bias in observations of 99942 Apophis (D. Tholen, private communication). In the discussions that followed, Tholen referred us to da Silva Neto et al. (2005), who had observed a mean declination bias of approximately 0.11 arcsec in the USNO B1.0 positions of the optical counterparts of 64 ICRF sources. Using the more accurate UCAC2 catalog as a reference, comparisons of the positions of stars appearing in both B1.0 and UCAC2 were used to derive local corrections to the B1.0 positions; implementing these local corrections, the B1.0 declination biases for the ICRF sources were reduced to approximately 0.03 arcsec. In time, this idea proved most useful.

3. The asteroid astrometric data

The Minor Planet Center (MPC), hosted by the Smithsonian Astrophysical Observatory at Harvard Univ., Cambridge, Mass., operates under the auspices of Division III of the International Astronomical Union as the clearinghouse for asteroid astrometric measurements, both optical and radar (Williams, 2009). As a part of this function, the MPC archives and distributes the available data on intervals of approximately one month.