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AUTOMATED DETECTION OF POTENTIALLY HAZARDOUS NEAR-EARTH OBJECT ENCOUNTERS

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EXTENDED ABSTRACT

Over the last two decades, there has been an increasing public and scientific awareness of the hazard posed by Near-Earth Objects (NEOs). Evidence has been gathered to support the claim that an extraterrestrial impact was responsible for large-scale extinctions at the boundary between the Cretaceous and Tertiary eras. More recently, evidence has been found to support the theory that the even larger mass extinction at the Permian-Triassic boundary resulted from an impact event. In response to increasing public and congressional interest, NASA has increased its funding of asteroid surveys, and adopted the goal of finding 90% of the kilometer-and-larger-sized asteroids by the year 2008. The latest population estimates for these objects indicate there are a total of about a thousand of these objects; only 50 percent of them have been discovered to date. During the course of these surveys, many hundreds of smaller NEOs have been found, and hundreds of thousands remain to be found in the size range which would survive passage through the atmosphere, should they be on collision course with Earth.

In order to evaluate the threat posed by known Near-Earth Objects, they must be tracked regularly, accurate orbits must be determined for each, and future close approaches must be predicted. Orbit determination for these objects is based almost entirely on optical astrometric observations: each observation consists of the right ascension and declination of the object at a specified time. Radar measurements (range and Doppler) are available for less than a hundred of these objects, but these data are also used in the orbit determination, when available.

The basic orbit determination problem is to estimate the object's six orbital elements $\mathbf{x}$ at some epoch t_0, given a set of astrometric measurements typically numbering in the dozens or hundreds. Once a preliminary orbit has been computed, usually from the first few of the observations, the problem becomes one of *orbit improvement* as additional observations are added to the data set. The problem is linearized about the previous best orbit estimate, and an improvement to the reference orbit is computed from the observation residuals (differences between the actual observations and predicted observations) via the linear method of least squares. The process is iterated until it converges, yielding the *nominal* orbit estimate $\hat{\mathbf{x}}$ and the associated covariance matrix $\mathbf{P}$.

An object's orbit is never known exactly, because the orbit calculation is based on imperfect measurements. The covariance matrix $\mathbf{P}$ quantifies the level of uncertainty in the orbit solution. A principal factor which determines the orbital accuracy of an asteroid or comet is the time span over which the object was observed, referred to as the *data arc*. A data arc of only a week to 10 days is very short, and will yield a fairly uncertain orbit; a data arc of a few months to a year would yield a moderately accurate orbit; and a data arc longer than a year or two should yield a fairly secure orbit. Secondary factors affecting the orbital accuracy include the number and precision of the observations, the object's proximity to the Earth when observed, and whether or not radar observations were used in the orbit solution.

At JPL, we have for decades computed the orbits for selected asteroids and comets, especially mission targets, and for several years, we have maintained an on-line database of NEO orbit solutions and close approach predictions. Recently, we have implemented a streamlined process for automatically updating orbital solutions for NEOs and detecting those objects that have an Earth collision probability greater than about 10^{-6}. Every day, new astrometric observations are automatically downloaded via Internet from the Minor Planet Center in Cambridge, MA. These are then merged into the observational datasets for the respective objects. Orbit solutions are then automatically updated for objects with new data, and future Earth close approaches of the nominal trajectory are predicted. The resulting sets of orbital elements and close-approach data are tabulated on the JPL Near-Earth Object web site (http://neo.jpl.nasa.gov).

Future close approaches are predicted over an interval of 50 to 100 years via numerical integration of the equations of motion. During this integration, the object's position relative to the Earth is monitored, and close approaches to within a threshold distance of 0.2 AU are detected. At each close approach, the so-called *b*-plane, or *impact plane* is computed, this being the plane perpendicular to the incoming asymptote of the hyperbolic geocentric trajectory. The geocentric position **b** of the intercept of the incoming asymptote on the impact plane is called the *impact parameter*. The object will impact the Earth if the magnitude of **b** is less than the capture radius for the encounter, given by

$$r_c = r_p \sqrt{1 + \frac{2\mu}{r_p v_\infty^2}}$$

where r_p is the radius of the Earth, μ is the gravitational parameter of the Earth, and v_∞ is the hyperbolic excess velocity of the encounter.

The computed value of **b** is uncertain due to uncertainty in the orbital solution used to start the numerical integration. A linear estimate of the uncertainty in **b** is provided by its 2×2 covariance matrix $\mathbf{P}_b$ which may be computed by mapping the orbital element covariance matrix **P** via the state transition matrix and the Jacobian matrix for the transformation to b-plane elements. $\mathbf{P}_b$ is a 2-dimensional marginal Gaussian probability density function, and is displayed graphically as an uncertainty ellipse in the impact plane. Even if the nominal solution does not lead to an impact, an impact is possible if any part of the uncertainty ellipse intersects the Earth disk. The probability of impact is estimated by integrating this marginal probability density function over the Earth disk.

The linearized b-plane analysis above will fail if the initial orbit solution is moderately uncertain, or the predicted close approach is quite far in the future (i.e. the prediction period covers many orbits of the object), or if the object makes intervening close approaches to any perturbing body. The main problem is that the uncertainties grow too large over the prediction interval, and the assumption of linearity in computing $\mathbf{P}_b$ no longer applies. Under simple Keplerian motion, position uncertainty along the orbit grows linearly with time, so that the uncertainty region after several orbits of prediction may subtend a fair fraction of the orbital circumference, or even wrap around on itself.

This leads to numerous problems. Part of the uncertainty region may experience close approaches to the Earth which go undetected because the nominal trajectory never approaches within the threshold distance of the Earth. In addition, even if the occurence of a close approach is properly detected, the part of the uncertainty region nearest the Earth may be so far from the nominal that linearity within the b-plane does not apply. Finally, some portions of the uncertainty region may experience localized close approaches, producing significant nonlinearities in the uncertainty region.

Monte Carlo techniques offer a robust approach for exploring the diverse set of possible trajectories which evolves from a domain of orbit solutions at an initial epoch. We have implemented two variations of the Monte Carlo technique for detecting possible close encounters with the Earth. In the first approach, the six-dimensional ellipsoid representing the uncertainty of the orbital elements at epoch is populated with thousands of random test points to create a set of initial conditions. In the second approach, we add thousands of different sets of random noise vectors to the observations themselves, and compute a new orbit for each case to obtain the set of starting conditions. In both of these approaches, each of the initial conditions is integrated forward over the time span of interest, and all close approaches are detected. The full nonlinear equations of motion are used in these integrations, so that dynamical nonlinearities are taken into account. The second method further takes into account nonlinearities in the orbit estimation process itself.

Our Monte Carlo analyses detect thousands of possible close approaches for some objects, especially those with uncertain orbits. The close approach data are collated and analyzed on the target plane for each encounter. Portions of the uncertainty region which lead to particularly close encounters can be explored in greater detail by densifying the Monte Carlo points and iterating to obtain initial conditions which lead to the closest possible approaches. Linearization about these cases is then used to estimate the probability of impact at each possible encounter. Automation of this entire process using robust algorithms is essential because of the large number of objects and close approaches that must be analyzed. This paper will discuss the techniques and algorithms used, and discuss several examples of asteroids which have been discovered to have significantly non-zero probabilities of colliding with the Earth. In most of these cases, subsequent observations have led to more precise orbital solutions and eliminated the possibility of collision.