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The Distribution of Required Deflection Impulses as a Function of Time Before Impact for Earth Impacting Asteroids

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We are building a precision cloud based asteroid orbit propagation and targeting capability that enables investigations of planetary defense questions requiring large computational resources. We use this to investigate the distribution of deflection ΔV required to deflect asteroids from hitting Earth as a function of time before impact. Starting from a population of 10000 virtual impacting asteroids (from Veres et al), we calculate at various times before impact the impulsive ΔV required to cause them to miss the Earth by a distance of 10 Earth radii. We find a large fraction of impacting asteroids are significantly easier to deflect than the mean, with more than an order of magnitude less velocity impulse required.

At larger times before impact, the fraction of these easily deflected asteroids increases. These easily deflected asteroids are found to have intervening close approaches with a planet (usually the Earth itself) prior to Earth impact which substantially reduces the impulsive deflection requirement (the real asteroid Apophis is a good example of such a case). At 30 years prior to impact, 5% of the impactors had a close approach (within a Hill radius) to a planet prior to impact. While these represent a small fraction of asteroid impact cases, we expect them to be overrepresented among the difficult deflection decision cases because they are also the asteroids which are observationally most difficult to rule out as impact threats. Our real world asteroid impact deflection scenario decisions are likely to be dominated by such cases.

1. INTRODUCTION Understanding the “delta-v” (ΔV) requirements to deflect an asteroid on a collision course with Earth is critical to Planetary Defense. The distribution of ΔV required is needed to understand the range of asteroid deflection scenarios. And, as described below, the ΔV required for deflection changes as a function of time and therefore the ΔV evolution over time is also needed for mission planning and launch window calculations. The mean ΔV required to deflect an asteroid from an Earth impact trajectory is ~3.5E-2 / t m/s where t is the lead time in years [1]. However, the actual ΔV required can vary greatly from the mean, depending upon the presence of intervening planetary close approaches and the

specifics of the impactor initial orbit. In this paper we investigate the distribution of ΔV required to deflect the asteroid as a function of the time before impact.

2. DESCRIPTION OF METHOD We start with the population of 10,000 virtual impactors described by Chesley and Spahr [2]. These virtual impactors represent the Earth-impacting subset of a larger total virtual asteroid population. These data include the heliocentric orbital elements for the asteroids 30 days prior to each impact. Using a solar system gravitational model described in section 3, based on information from Veres [3] these elements are slightly altered using a differential correct (i.e. “shooting method”) targeter to come up with modified elements that hit the same targets (in impact time, Latitude and Longitude) using the newer solar system model. This creates a new set of elements that are consistent both with the distribution of Chesley and Spahr [2] and also with the newly constructed model. Once the initial states are created the virtual asteroid orbits are propagated backwards in time (from the 30-days-to-impact point) 50 years to create a high-fidelity ephemeris. 2 ΔV calculation process We automated the process of calculating the ΔV using a software script which selects initial states from the 50-year ephemeris. The script scans along the ephemeris in time, selecting an maneuver position & velocity state at two month intervals. At each of these states the script runs STK/Astrogator to calculate the ΔV necessary to change the encounter from an impacting trajectory to a 10 Re perigee altitude flyby. We call each scan of a trajectory the "ΔV profile" of that specific asteroid. Representative ΔV profiles Figure 1 shows four such profiles for asteroids from our modified population. Asteroids 1,2 and 4 demonstrate an osculating ΔV requirement. This comes from sampling the ΔV every 2 months, rather than precisely at the correct location for a diversion maneuver.

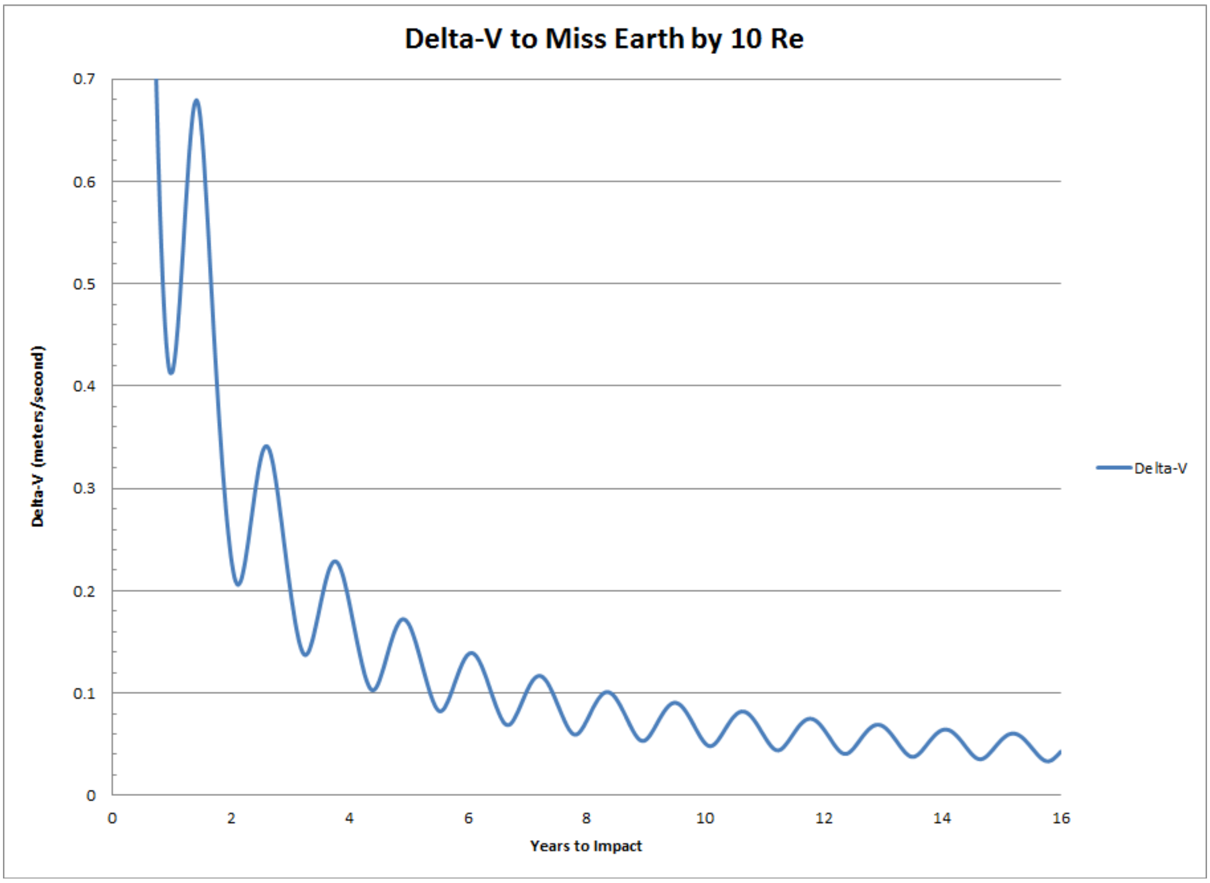

Figure 1: Typical deflection delta V as a function of time prior to impact

3. SOLAR SYSTEM MODELING The B612 Asteroid Institute, in cooperation with Analytical Graphics Inc. (AGI), is creating a cloud-based asteroid propagation capability for asteroid orbit studies based on AGI's Systems Tool Kit (STK) Components Segmented Propagation Library [3] and Google's cloud-based computing architecture. This capability will support large scale analysis of synthetic asteroid populations and potential impacts, enabling quick, high-precision generating of these populations. We are planning to use a RESTful API so the system will be available to external analysis toolsets. The first step in implementing this system is to match a desktop-based high-fidelity STK/Astrogator simulation with JPL's online "Horizons" system. Once this is accomplished, the modeling setup can be duplicated on the cloud side, and the API can be tested and brought on-line.

AGI's commercial software module "Astrogator", which is part of the STK software suite [5], has heritage from the Goddard Mission Analysis System, (GMAS) and an early variation on the General MANeuver program (GMAN), as well as the Mission Analysis and Trajectory Design Tool "Swingby" [6]. Since its release as part of STK in 1998, STK/Astrogator has been used internationally for pre-launch mission analysis and in operations on numerous commercial and government Earth-Orbiting, Lunar, and deep space missions, including NASA's WMAP, CONTOUR, DISCOVR, LCROSS, IBEX, LADEE, LRO, MAVEN, MESSENGER and New Horizons.

The NASA/JPL on-line Horizons system provides numerically integrated asteroids based on orbit solutions and standardized force models. SPK files can be created from Horizons as a form of output from the integrator. The Horizons integration settings and force models match those used in creating the DE430/431 planetary ephemerides [10] and were communicated by Giorgini to the authors [8]. It uses a heliocentric point-mass model of the Sun and 3rd body planetary system barycenters for all the planets (including Pluto) plus the Earth and Moon. Within 0.01 AU of Earth, an analytical Earth J2 oblateness model is also used. General relativity is modeled along with perturbations from the sixteen largest asteroids: 1 Ceres, 2 Pallas, 4 Vesta, 10 Hygeia, 3 Juno, 6 Hebe, 7 Iris, 15 Eunomia, 16 Psyche, 29 Amphitrite, 52 Europa, 65 Cybele, 87 Sylvia, 88 Thisbe, 511 Davida, and 704 Interamnia. Non-gravitational parameters A1-A3, DT and related model parameters modeled as described in are as described by Yeomans [10]. This force is a numerical approximation of the Yarkovsky effect.
To match the JPL Horizons models, STK/Astrogator's numerical integration of the heliocentric asteroid orbits must account for close approaches with other solar system bodies. Therefore we are using an numerical integrator with automatic step-size control, a dual-order Runge Kutta Fehlberg 7(8) Integrator. This integrator calculates two estimates of the next orbit state, and compares the difference to a specified error tolerance. If the error is too great, the step is thrown away, the step size reduced, and the step taken again. This then mitigates the effect of truncation error. If the error is too small (because of a too-small step) the step is accepted, and the step size increased for the next step. This improves efficiency by taking the largest step possible within error tolerances, and it reduces the effect of numerical round-off errors. The numerical integration is performed in a Sun-centered International Celestial Reference Frame (ICRF), using the point masses of the solar system bodies described above. General Relativistic effects are added in accordance with IERS Technical Note 32, IERS Conventions (2003) and a Yarkovsky force model was added to match Yeomans [9] We selected to use these techniques in STK/Astrogator, and are currently implementing the same with STK Components using the Google cloud infrastructure.

4. MATCHING OF CHESLEY/SPAHR POPULATION Because the Chesley Spahr population was created in the late 1990's it wasn't modeled with the current JPL force model. For instance, they used the DE405 values (the most recent at the time). We decided to use the DE430 ephemeris with all the planets, the Moon, three asteroids (Ceres, Pallas, and Vesta), and General Relativity. These differences in force model were the reason we re-calculated the initial states. To do this, we used the initial position and velocity states from the Chesley/Spahr population with epochs at 30 days before Earth impact. Using STK/Astrogator we calculated the three components of a delta-V needed to hit the same latitude, longitude, and altitude at the same epoch as the population. These ΔV's needed for this correction are very small, on the order of mm's per second. We automated this process and derived new states for the entire population.

5. DISTRIBUTION OF DEFLECTION ΔV: We calculated the deflection delta V as described above for the population of 10000 impacting asteroids. In figure 2 we plot the distribution of deflection delta V when the impulse is applied 30 years prior to Earth impact. As can be seen, a subset of asteroids requires more than an order of magnitude less deflection delta V than the mean. In figure 2 we highlight asteroids

(shown in blue) which have an intervening close approach prior to their Earth impact. Here we have defined a close approach as coming within a Hill radius of a planet. This represents 518 of the 10000 total asteroids, or about 5%. The vast majority of the intervening close approaches were with Earth.

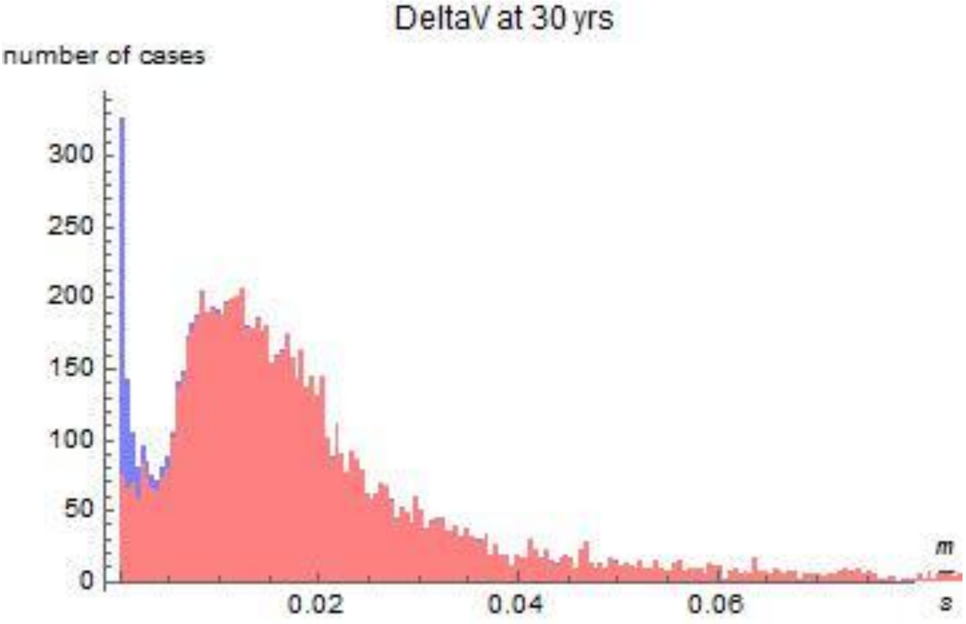

Figure 2 – The distribution of deflection delta V targeting 10 Earth radii miss distance when applied 30 years prior to impact. In red are asteroids without intervening close approaches. In blue are asteroids with intervening close approaches.

In Figure 3 we show the delta V distribution just for the asteroids with intervening close approaches. We point out that while these asteroids are easiest to deflect (given their smaller deflection delta V), they are also the asteroids whose orbits must be determined most accurately in order to know if they are going to hit Earth. These asteroids will the subject of further investigations where we use our cloud based asteroid orbit software to model the impact probabilities as a function of time for simulated observations.

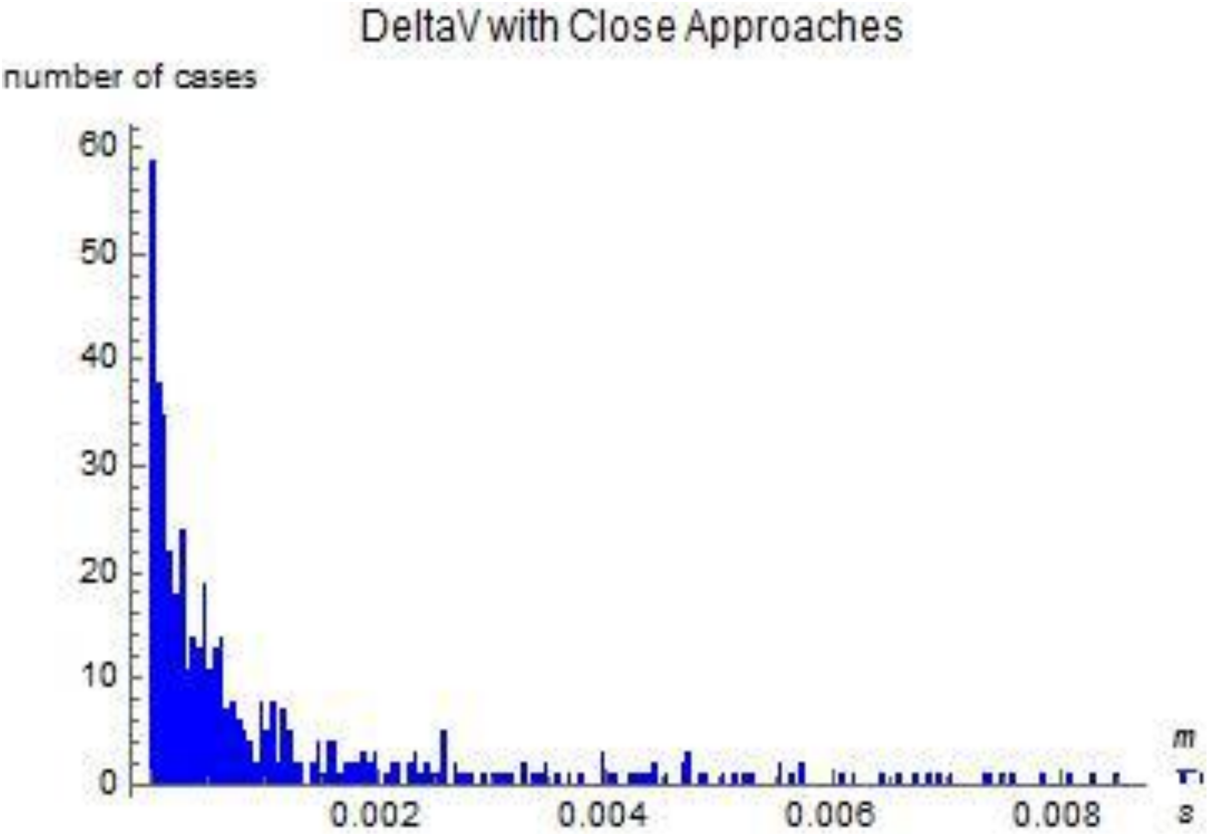

Figure 3 – Distribution of deflection deltaV for the subset of impacting asteroids with intervening close approaches.

7. SUMMARY – We are building a cloud based asteroid orbit analysis system. It can be used to address questions requiring large computational resources such as finding the distribution of deflection delta V as a function of time prior to impact.

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