KEYHOLES AND JABBAS: THE ROLE OF PRE-IMPACT CLOSE APPROACHES IN ASTEROID DEFLECTION. P. W. Chodas[1], [1]Jet Propulsion Laboratory, California Institute of Technology, MS301-121, Pasadena, CA 91109.

The problem of how to deflect a threatening Near-Earth Object on a "direct" collision course with the Earth is fairly well understood: the plan would be to apply a velocity change in the along-track direction, so that over time the asteroid would move far enough ahead or behind its original trajectory that it would miss the Earth. It is quite likely that the deflection would have to be applied many years and many asteroid revolutions before impact, so that the small velocity change would have enough time to move the asteroid the necessary thousands of kilometers along its orbit by the time of the potential impact. There is, however, a good chance that the NEO would make one or more Earth close approaches during this intervening time: these can significantly affect the outcome of the deflection and must be considered when developing deflection strategies.

The possible 2036 impacting trajectory for Apophis is a great example: this trajectory makes an extremely close Earth encounter seven years before impact, passing through a 600m-wide keyhole in the 2029 target plane. A keyhole is a narrow slice of the uncertainty ellipse in the target plane at a position where the encounter perturbs the object onto a trajectory which impacts at a later time. Passage through the keyhole implies impact, and conversely, deflection away from the keyhole implies avoidance of the impact.

Since keyholes are typically narrow, it is in principle easier to deflect the object before keyhole passage rather than after: the trajectory needs to be shifted a shorter distance. Even though this comparison is measured in different target planes at different times, the comparison is still valid, and it is generally preferable to deflect the asteroid before the keyhole passage. The keyhole provides deflection "leverage"; it amplifies the along-track displacement caused by the deflection. The leverage provided by a keyhole can be roughly defined as the ratio of the chord length across the Earth disc in the impact target plane to the width of the keyhole in the pre-impact target plane.

Because the 2029 Apophis Earth encounter is so close, the 2036 keyhole is particularly narrow, and it therefore provides a huge leverage factor, over 30,000. But how common is this scenario? What is the chance that a random impactor will have keyhole passages with such large deflection leverage? How much leverage will more typical distant pre-impact close approaches provide? How wide can keyholes get? Are there other scenarios in which pre-impact close approaches have the opposite effect, reducing the effect of prior along-track deflections instead of amplifying them?

We answer these questions statistically by studying deflection leverage within a set of nearly 1000 simulated impactors [1]. All pre-impact Earth close approaches within 0.2 AU during the 50-year period leading up to impact for each of these impactors were analyzed, a total of nearly 3500 cases. Ahead of each close approach, a series of test points was set up along the line of variations, and the points were numerically integrated to the impact target plane. Iteration within the set was used to find bounding trajectories leading to impact. The separation between the bounding trajectories in each of their pre-impact target planes was then used to compute the deflection leverage of each of the pre-impact close approaches.

Results of the study indicate that large-leverage pre-impact close approaches such as that of Apophis in 2029 are extremely rare. Only about 8 percent of the impactors had keyhole passages providing a leverage factor of 10 or larger within 25 years of impact, and that fraction decreased to 3 percent for leverage factors greater than 100. The fraction for leverage factors greater than 1000, such as Apophis in 2029, was well below 1 percent.

The study also indicated the prevalence of the converse effect produced by distant pre-impact close approaches, large regions in the target plane we have nicknamed "jabbas". Passage through a jabba has the undesirable property of subverting deflection attempts by reducing or absorbing the effect of a prior deflection, quite the opposite of the amplification provided by a keyhole. Deflection of these impactors may be easier to accomplish after the asteroid's pre-impact encounter, rather than before as with keyholes. About 8 percent of the simulated impactors had jabbas which reduced deflection by at least a factor of 10, while the fraction with jabbas which reduced deflection by a factor of 100 was well below 1 percent.

References: [1] Chesley, S.R, and Spahr, T.B., Earth impactors: Orbital characteristics and warning times, in *Mitigation of Hazardous Comets and Asteroids*, M.J.S. Belton *et al.*, *eds*, 2004.