An Online Educational Tool for Near-Earth Object Mitigation Mission Design

1. Introduction

Suppose a Near-Earth Object (NEO) is on a collision course with the Earth. How could we prevent it from impacting our planet? Numerous concepts have been proposed for deflecting an asteroid away from a collision trajectory using technologies such as solar concentrators, lasers, rocket engines, explosives, or mass drivers. But the best and most reliable deflection technique could well be the simplest one of all: knocking the object off course by hitting it at high speed with a large impacting spacecraft. In fact, the navigational expertise required for this type of mission was already demonstrated when the Deep Impact spacecraft was purposely slammed into the nucleus of comet Tempel 1 on July 4th 2005.

The NEO Deflection App is a web-based educational tool designed to demonstrate the basic concepts involved in deflecting an asteroid away from an Earth impacting trajectory by hitting it with an impactor spacecraft. Since we have made a number of simplifying assumptions in designing this application, it is really only for educational use. Nevertheless, the asteroid trajectory dynamics are very realistic, as are the calculations of the amount by which this trajectory moves during the Earth encounter as a function of the velocity change that occurs when the spacecraft impacts the asteroid many days, months or years earlier.

The application is pre-loaded with a number of simulated asteroids, all on Earth-impact trajectories. *These are not actual known asteroids – they are all simulated!* Even though they are hypothetical, however, the trajectories are realistic and representative of what we would expect for possible real Earth impactors. Most of the trajectories we have selected are of the "Apollo" orbit type, which means they have orbital periods greater than 1 year, but some are of the "Aten" type, with periods of less than 1 year. The orbits have a variety of inclinations relative to the ecliptic plane (the plane of the Earth's orbit). Some have close encounters with the Earth prior to impact, producing "keyholes" that provide opportunities for amplifying the effects of deflections that take place prior to these close Earth approaches.

2. General Description of the NEO Deflection Tool

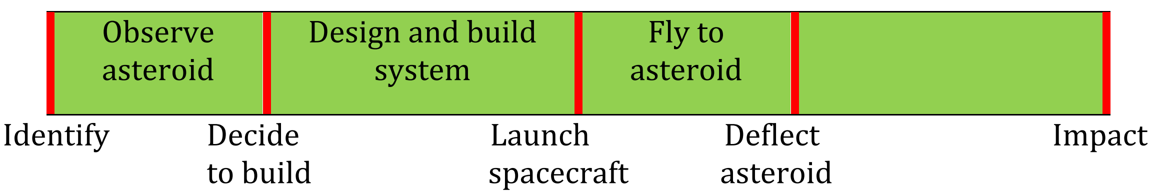
The NEO Deflection Application is located here: http://neo.jpl.nasa.gov/nda.

The app has two modes, reflecting two separate parts of the mission design problem for an asteroid deflection mission.

- The "Delta-V" mode addresses just the changes in the asteroid's velocity that are required to prevent it from impacting Earth. In this mode, you focus on finding the best time to deflect the asteroid, as well as the necessary size of the velocity change and the direction in which to apply the change to avoid the Earth collision.

- The "Intercept Mode" of the application allows you to focus on the details of how to achieve the desired deflection: you first specify the available launch vehicle and number of launches, and the asteroid's size, density and the so-called momentum multiplier (β, beta). Then you select the Time of Deflection (D) relative to the potential Earth impact date. Finally, you select the Transfer Time, the interval between the spacecraft launch and the deflection (L-to-D). If your mission meets all the launch constraints, the application calculates the trajectory that will take your spacecraft from the Earth to the asteroid, determines the mass of your spacecraft as the maximum the launch vehicle can launch onto your trajectory, computes the velocity change your interceptor will impart to the asteroid (both size and direction), and shows you how much the asteroid's trajectory will change. In particular, the app tells you whether the deflection mission you have designed would successfully deflect the asteroid away from Earth with the inputs you provided.

The following graphic timeline outlines the realistic steps that would have to be taken from the realization that an object will impact Earth to the design and launching of a KI spacecraft to collide with, and deflect the asteroid; only the Launch, Deflection and Impact times are used in the app.



3. Description of Terms

This section provides a description of some of the terms used in discussing asteroid orbits and encounters, and designing asteroid deflection missions.

Orbital parameters or **orbital elements**: Six parameters are used to define the object's instantaneous elliptical orbit about the Sun. We say "instantaneous" because the orbit can change over time, mostly due to gravitational perturbations caused by the planets. The particular instant of time at which we specify orbital elements is called the epoch of osculation, or simply "epoch;" in this application, we provide the orbital elements at the time of deflection. The six orbital parameters are:

- Semi-major axis a: half the length of the major axis of the asteroid's elliptical orbit about the Sun. It is also called the "mean" orbital distance of the asteroid from the Sun. It is given in astronomical units (au), where 1 au is the approximate mean distance of the Earth from the Sun (149,597,870.7 km, 92,955,807.3 miles),
- Eccentricity e: a measure of the ellipticity of the orbit (anywhere from zero for a circular orbit to nearly 1 for a highly elliptical orbit),

- Inclination *i*: angle between the asteroid's orbital plane and the ecliptic plane (the plane of the Earth's orbit),
- Longitude of the ascending node *Ω*: angle in the ecliptic plane between the x-axis and the line through the ascending node (the point where the asteroid crosses through the ecliptic plane in the ascending +z-direction),
- Argument of perihelion *ω*: angle in the asteroid's orbit plane between the ascending node and the perihelion point (the point on the orbit closest to the Sun),
- True anomaly *ν*: the angle in the asteroid's orbital plane between the perihelion point and the current location of the asteroid,
- Orbital period *P*: the time it takes the asteroid to make one complete revolution around the Sun. The orbital period is not one of the six independent orbital elements since it can be computed from the semi-major axis.

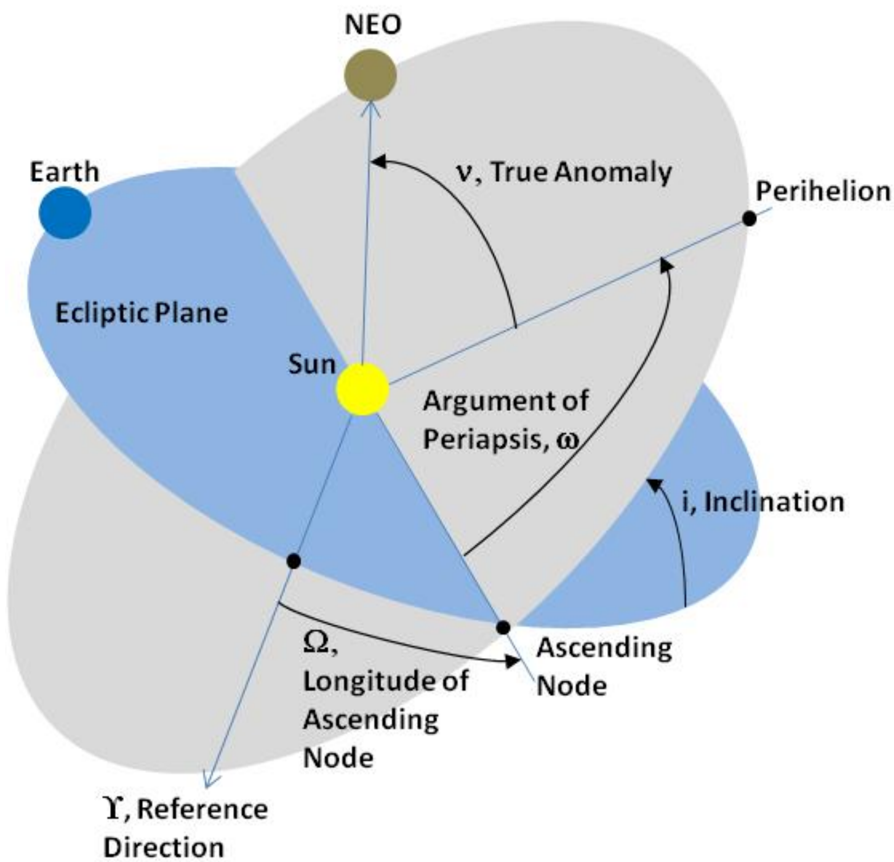


Figure 1. The angular orbital elements.

ACN coordinate system: A coordinate system set up at the center of mass of the asteroid at the time of deflection and used to express the magnitude and direction of the velocity change imparted to the asteroid. Its principal directions are:

> Along-track direction (**A**): in the asteroid's orbital plane and along the direction of the asteroid's current velocity vector about the Sun (**v**),
>
> Normal direction (**N**) perpendicular to the asteroid's orbit plane and aligned with the positive orbital angular momentum vector (**r** x **v**), where **r** is the vector from the Sun to the asteroid's current position,
>
> Cross-track direction (**C**): in the orbital plane, perpendicular to the along-track direction (**C** = **N** x **A**), and positive in the general direction of the Sun.

$\mathbf{V_\infty}$ (**V infinity**): Velocity of the asteroid relative to the Earth during a close approach or potential impact, with the acceleration caused by the Earth's gravity removed. This can be thought of as the incoming velocity of the asteroid with respect to the Earth, when it is still far away from the Earth (i.e., at an infinite distance). This parameter is sometimes called the hyperbolic excess velocity of the asteroid.

$\mathbf{V_{s,out}}$ (**V infinity**, outbound): The hyperbolic excess velocity of the spacecraft after launch when it has left the Earth's sphere of influence and is headed towards the asteroid. Note that this value is not shown by the tool.

$\mathbf{V_{rel}}$: The velocity of the KI spacecraft relative to the asteroid when the KI spacecraft arrives at the asteroid, i.e., at the Time of Deflection D.

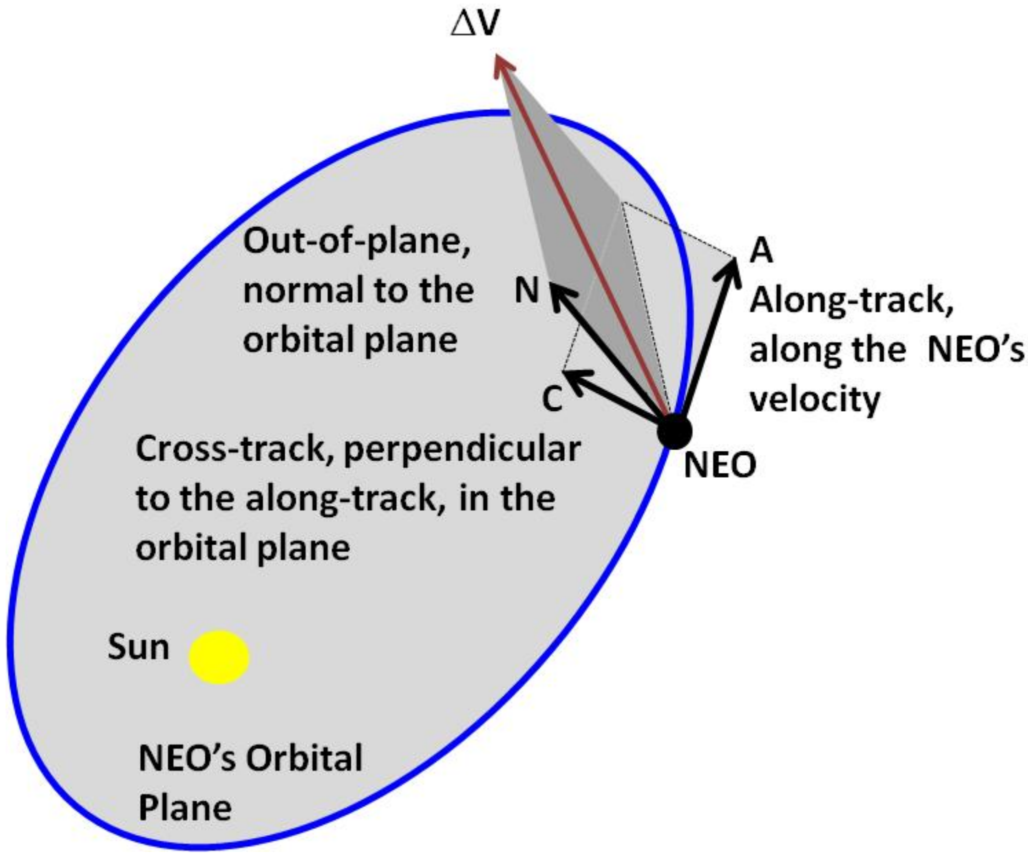


Figure 2. Diagram showing the ACN coordinate system

B-plane or **Earth Target Plane**: When an object in orbit about the Sun encounters the Earth, it follows a curved hyperbolic trajectory relative to the Earth, with bending caused by the Earth's gravity. The B-plane is defined as the plane through the Earth's center perpendicular to the asymptote of the incoming leg of the hyperbolic trajectory. *The position of the point where the approach asymptote intersects the B-plane characterizes the asteroid's encounter trajectory.* The B-plane is so named because it contains the vector **B**, which is the position of the asymptote intersection point relative to the Earth's center. A successful asteroid deflection will change the asteroid's trajectory in such a way that the position of this point in the B-plane moves outside the capture circle.

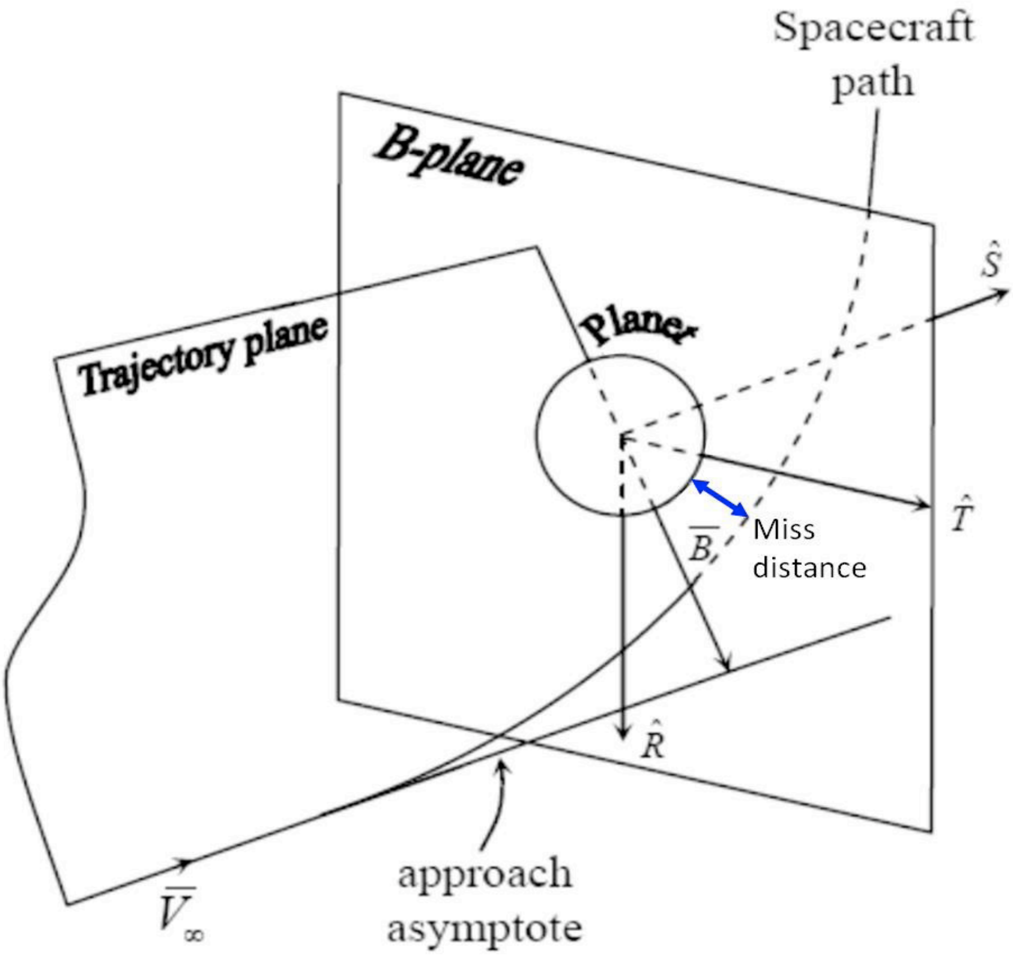


Figure 3. Approach asymptote, B-plane and B-vector.

Note that due to the pull of the Earth's gravity, the point of closest approach is actually *closer* to the Earth's center than the distance B. We prefer to deal only with the approach asymptote and to represent the asteroid's trajectory as a point in the B-plane because the relationships are simpler when the variable effects of the Earth's gravity are removed. In particular, the relation between an applied deflection impulse (ΔV) and the position change on the B-plane is essentially linear. If the deflection impulse is doubled, for example, the position change on the B-plane would be about twice as large.

Capture radius (R_c): The radius of the capture circle in the B-plane. The capture circle is traces all the trajectories which will have Earth-grazing close approaches. If the asteroid trajectory is inside the capture circle, the asteroid will collide with the Earth. The capture radius (R_c) depends upon the incoming object's velocity (V_{in} = incoming $V_{a,\infty}$) and the mass (M) of the Earth. In terms of the body radius (R_b), the capture radius (R_c) can be expressed as:

$R_c = R_b\{[2GM/R_bV_\infty^2] + 1\}^{1/2}$

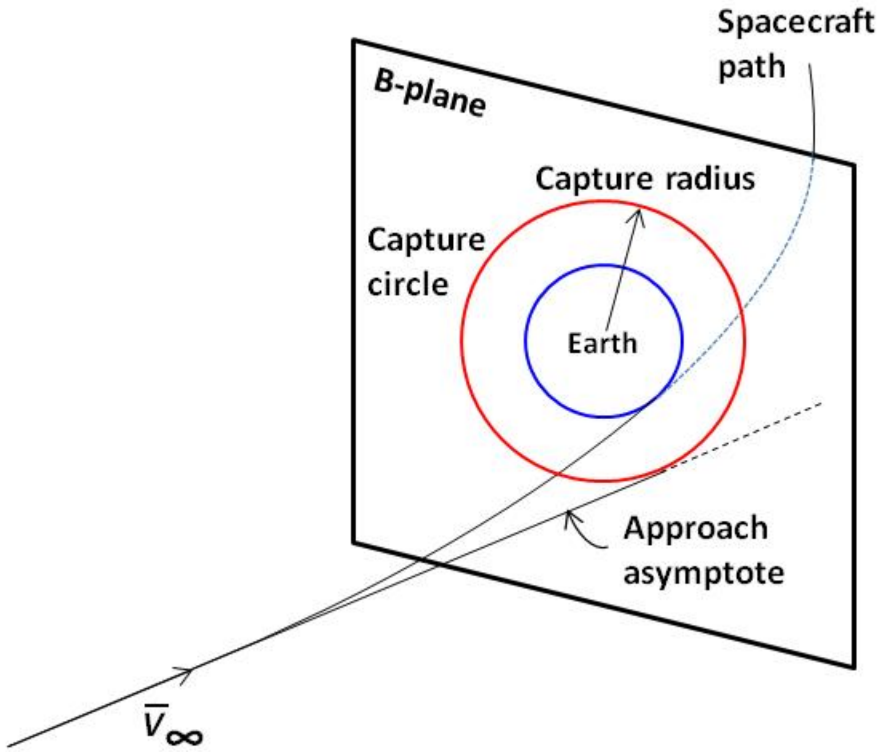


Figure 4. The Capture radius and capture circle

Perigee Distance: The distance from the Earth's center to the asteroid at its closest approach point, also called the Close Approach Distance. If this distance is less than 1 Earth radius, the asteroid will collide with the Earth (the value is calculated as if the Earth were a point mass).

ΔV (Delta V): The change in the asteroid's velocity due to the impact of the spacecraft. Since the change occurs almost instantaneously, it is often referred to as a velocity *impulse*. It is a vector with both a size and a direction (see Figure 1); its components in the along-track, cross-track and normal directions are denoted ΔVA, ΔVC and ΔVN, respectively.

C3: The launch energy-per-unit-mass of the KI spacecraft as it departs the Earth on its interplanetary trajectory. Once you set the Time of Deflection D and the Transfer Time L-to-D, It is computed as the square of the outbound hyperbolic excess velocity ($C3 = V_{out}^2$ where V_{out} = outgoing $V_{s,\infty}$). Each launch vehicle has a maximum C3 it can deliver for a given payload mass. Conversely, for the C3 required by a given trajectory, each launch vehicle has a maximum mass that it can launch. If the interceptor mass is not large enough to deflect the asteroid enough, multiple KI missions with multiple launches may be required.

β (Beta): The momentum multiplier factor that accounts for the additional momentum delivered to the asteroid due to ejecta blowback when the KI spacecraft impacts. The ejecta is the asteroidal material that rebounds after impact and is thrown back in the direction from which the incoming spacecraft came. If m and M are the masses of the impacting spacecraft and the asteroid, respectively, then $\Delta V = \beta V_R m/M$. The size of this beta (β) factor is uncertain to a large extent, as it depends on the impact velocity as well as the composition and porosity of the asteroid, but it is likely to be within the range from 1 to 9. A value of beta (β) = 1 indicates a "plastic" collision in which the impactor is absorbed into the body with no ejecta, while β=2 represents an "elastic" collision in which the additional momentum provided by the ejecta is equal to the spacecraft impactor momentum; $\beta > 2$ represents a "super-elastic" collision. We do not consider impacts with $\beta < 1$; this might occur if ejecta material is spalled from the side of the asteroid opposite to the spacecraft impact point. The ejecta would then introduce momentum counter to that created by the spacecraft impact. This type of "sub-plastic" collision is considered unlikely.

4. Description of the NEO Deflection App Screen

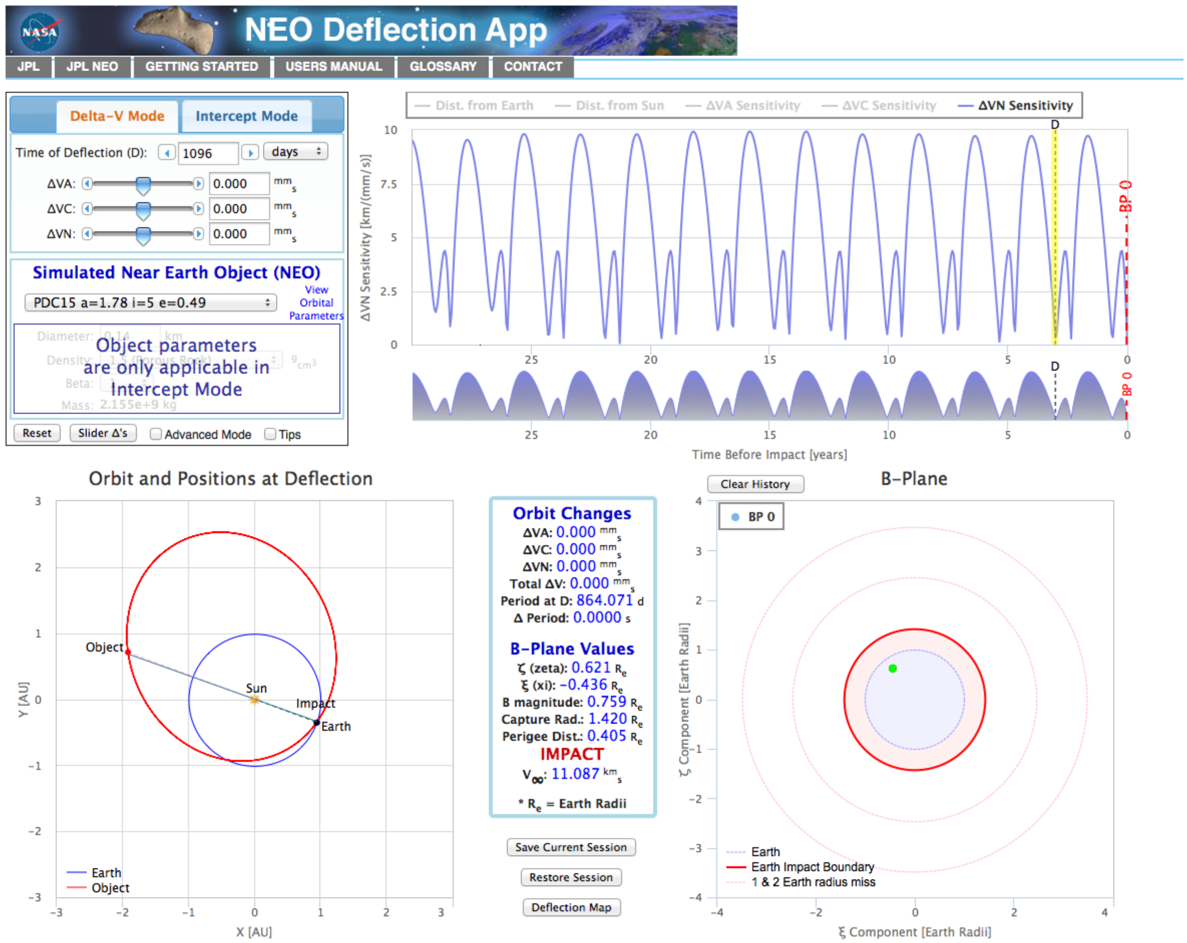


Figure 4. The NEO Deflection App Screen

The app screen displays the following five panels for each of the two selectable modes, Delta-V Mode and Intercept Mode:

Main Panel: The rectangular box in the upper left where the main inputs to the app are set. For example, the object to be deflected is selected from a pulldown list of simulated impacting objects. Short descriptive labels are provided, giving values for the key orbital elements, semi-major axis (a), the orbital inclination (i), the eccentricity (e) and an indication whether or not the object passes through a keyhole [kh]. See Section 6 for a discussion of "keyholes." At the top of Main Panel are tabs which select one of two modes: Delta-V Mode or the Intercept Mode.

Delta-V Mode: When the app is in this mode, you specify the Time of Deflection (D) and the three components of the deflection you wish to apply at that time: ΔVA, ΔVC and ΔVN. The app will show you whether these inputs are sufficient to make the asteroid miss the Earth. The Time of Deflection (D) is the time at which the asteroid is deflected, relative to the potential impact time. This key parameter can be adjusted by clicking the increment or decrement buttons, or by entering a value in the text box. You can also set D by clicking at the appropriate hoizontal position in the Plot Panel, or by dragging the Object to the appropriate position in the Orbit Panel (see below).

The ΔV values applied at the time of deflection (D) can be set via slider bars, increment and decrement buttons, or by entering values in the text boxes. The total magnitude of the ΔV, the resultant change in orbital period and the resulting trajectory's B-Plane coordinates are then displayed in the Values Panel in the middle of the bottom half of the page. If the trajectory still impacts the Earth, the word IMPACT will be displayed; otherwise, the miss distance will be shown. A graphical representation of the current trajectory position is shown as a green dot in the B-Plane Panel in the bottom right of the screen. When the green dot lies inside the red capture circle, the trajectory will impact. The red dot shows the undeflected trajectory.

Intercept Mode: When the app is in Intercept Mode, you design a Kinetic Impactor (KI) interceptor mission to deflect the asteroid. You specify the Time of Deflection (D) as before, but now you also specify the Transfer Time, basically the flight time of your interceptor, from Launch to Deflection (L to D). The app adds the D value to the L-to-D value, to get the launch time, L, and then, using the position of the asteroid at Deflection, position of Earth at Launch, and the flight time, it calculates the transfer trajectory and the Earth departure C3. You also need to specify the launch vehicle for your interceptor, and the number of launches, and from this the app calculates the total mass of your interceptor(s). For simplicity, multiple launches are assumed to all occur on the same day and collide with the asteroid on the same day. The app defaults to a single launch of an Atlas 551 launch vehicle.

In this mode, you must also provide information about the object's physical properties, the Mean Diameter, bulk density, and the Beta factor, which accounts for the effects of the ejecta from the impact. Once you have entered these values, the application calculates the asteroid's mass (assuming a spherical shape), the components ΔVA, ΔVC and ΔVN of the deflection the interceptor will apply to the object, and finally the updated Perigee Distance at the time of the potential impact. Only specific combinations of Deflection time D and the Transfer time (L to D) will produce valid interceptor trajectories that also satisfy launch vehicle constraints, and these value combinations are not always easy to find.

Clicking the "Reset" button at the bottom of the Main Panel clears all input data. Clicking the "Slider Δ's" button brings up a dialog box in which you can change the increments on the parameters controlled by the sliders. The "Advanced Mode" checkbox gives you more flexibility in selecting inputs. For example, you could select multiple launches from different launch vehicles (Atlas 551, Delta IV Heavy, or a Falcon 9 Heavy), or you could specify the number of revolutions about the sun for the Lambert solution (see Appendix A), or you could set specific values for beta and the bulk density instead of picking values from a pulldown list. Checking the "Tips" box will cause the app to provide short explanatory tool tips when you hover the pointer over various items on the screens.

Plot Panel: An elongated box in the upper right of the screen providing plots of the following parameters as a function of time before impact:

- Earth-to-object distance in astronomical units (AU)
- Sun-to-object distance in astronomical units (AU)
- The sensitivities of the total B-Plane deflection to ΔVA, ΔVC and ΔVN as a function of the deflection time D. The units for the Y-axis of these plots are kilometers per millimeters/second. Placing the deflection time D atop a curve peak will help optimize the amount of deflection you get for that particular Delta-V component.

The plot covers up to 30 years prior to the potential Earth impact, but you can zoom in on any portion of it by dragging across a time range of interest; a small full-scale version of the plot is provided along the bottom of the Panel for context. If you have zoomed in on a plot, you can zoom back out to full range by clicking the "Reset Zoom" button in the upper right of the plot. At the far right hand side of the plot, the dotted red line marked BP 0 denotes the potential Earth impact time. A later discussion in Section 6 will explain the so-called keyhole times that are denoted by BP 1, BP 2, etc. for some objects.

The dotted yellow vertical line marked D indicates the currently selected Time of Deflection and in Intercept Mode, the dotted blue line denotes the launch time (L). When you hover the pointer over the upper plot, a floating dot and information box appears shows you the nearest data point values; if you click on the point, you move D to that horizontal location. You can also drag these lines to change the values of D and L. The default plot in this panel is the Earth-to-Object distance, but that can be switched to the Sun-to-Object distance or any of the three sensitivity plots by clicking the desired plot name along the top.

Orbit Panel: A square plot labeled "Orbit and Positions at Deflection" shows the orbits of the object (in red) and the Earth (in dark blue). The positions of the object and Earth at the time of deflection are shown as dots in the same respective colors. The positions of the asteroid and Earth at impact are denoted by a black dot. Note: the blue dot may be hidden behind the black dot at the default deflection time, since the default is exactly 3years before impact, and the Earth will be at the impact position 3 revolutions before impact.

In Intercept Mode, the interceptor transfer trajectory is displayed as a dashed green path, and in the bottom right hand corner, the orbital inclination of the interceptor spacecraft is given along with the number of orbits about the sun it takes prior to the deflection. This latter number can be input explicitly in Advanced Mode.

Values Panel: In this box, the changes to the asteroid's orbit caused by the deflection are displayed, including the velocity changes at time of deflection (ΔVA, ΔVC and ΔVN), the total velocity change (Total ΔV), the asteroid's orbital period at the time of the deflection, and the change in this period due to the deflection maneuver (Δ Period). The B-plane coordinates (described below) are also shown, along with the Earth's capture radius, the asteroid's perigee distance and the relative Earth-asteroid velocity at impact ($\mathbf{V}_\infty$), without consideration of the Earth's gravity. In Intercept Mode, the required energy-per-unit-mass (C3) that the launch vehicle must supply to put the spacecraft on the intercept trajectory is also given along with relative velocity and phase angle (Sun-asteroid-spacecraft) at the intercept point (the phase angle is important for terminal spacecraft navigation considerations).

Below the Values Panel box are three buttons that allow you to save and restore information on session scenarios, and to display a deflection map that can be used as an aid for finding effective combinations of spacecraft Transfer times and Deflection times. For each value of the deflection (D) and transfer time (L to D), the map provides a unit-less and normalized measure of the size of the deflection in the B-plane, increasing from dark blue to red. A series of four panels are used to cover the full thirty year time period.

B-Plane Panel: A plot showing the location of the asteroid's trajectory in the Earth impact B-plane. The coordinate axes are called ξ (xi) and ζ (zeta), and the units are Earth radii. It turns out that the ζ (zeta) direction is the easier direction in which to move the asteroid because it is closely associated with the asteroid's heliocentric along-track direction. The filled blue circle indicates the size of the Earth, the red dotted circle indicates the capture radius for the encounter, the red dot indicates the trajectory of the undeflected asteroid, and the green dot indicates the current trajectory of the deflected asteroid. If a green dot is within the red circle, the asteroid will hit the Earth. The goal, then, is to find settings that move the green dot outside the red circle. Blue/purple open circles indicate your previous trajectories (i.e., those with previous deflection settings).

If the green dot is a large distance from the Earth (the asteroid will miss Earth by a wide margin), the scale of the diagram will adjust accordingly. You can zoom in on a region of the B-plane by dragging the pointer over our region of interest. You can reset the zoom by clicking the "Reset Zoom" button above the B-Plane Panel. Clicking "Clear History" will delete all but the current position (i.e., green dot) of the B-plane encounters.

The ξ- and ζ-coordinates of the current trajectory (green dot) are displayed in the Values Panel.

Some of the objects pass close enough to the Earth during the 30 years before its impact that they will pass through keyholes. Additional B-planes are set up for each of these pre-impact encounters, and we label them BP 1, BP 2, etc. to distinguish them from the B-plane at the potential Earth impact, BP 0. You can display a pre-impact B-plane by clicking on its name (e.g. BP 1) in the legend at the top of the panel. In these secondary B-planes, the app zooms in on the keyhole: the boundaries of the keyhole are shown by the two solid purple lines. Trajectories passing between these lines will impact the Earth later, at BP 0. To avoid impact, your KI mission must move the trajectory outside this line pair. The width of the keyhole is vertical (zeta) distance between the line pair, and it is usually much smaller than the diameter of the Earth. That's why a deflection before keyhole passage is highly effective: you don't have to move the trajectory much to avoid the impact in BP 0. If you click Reset zoom, you can see the location of the keyhole with respect to the Earth at the close approach. The outer bounds of the keyhole turn out to be large circles that pass near the center of the Earth. To get back to the zoomed-in view of the keyhole, drag the mouse diagonally around the green or red dots a few times. A more complete discussion of keyholes is provided in Section 6.

5. Detailed Guide and Examples

a) Guide for Delta-V Mode:

In this mode, you have complete control over the size and direction of the deflection impulse and when this deflection is to be applied to the asteroid. You can thus get a good feeling for the best direction to apply the deflection, as well as the best time to apply it. You might have to use a trial and error technique to find good values for D and the ΔV's. Here are some general rules that you can use in selecting your inputs:

- Except possibly for very short warning time encounters when the Earth impacting asteroid is less than one revolution about the Sun away from Earth impact, the Spacecraft deflection velocity impulses are more effective in the along-track direction (ΔVA) rather than in the cross-track (ΔVC) or out-of-plane normal (ΔVN) direction.
- An along-track ΔVA is more effective in adjusting the asteroid's orbital energy, leading to a slight change in its semi-major axis. For example, if the spacecraft is overtaken by a faster near-Earth asteroid (a head-on collision), the asteroid will lose orbital energy and have its semi-major axis reduced accordingly. Likewise, if the spacecraft rear-ends the asteroid, the asteroid will gain orbital energy and have its semi-major axis increased. A change in the asteroid's semi-major axis is reflected as a vertical position change (ζ) in the B-plane Panel.
- Deflections that take place near the asteroid's perihelion and in the asteroid's along-track direction will generally be the most effective.
- It is generally best to deflect the asteroid early so that there is as much time as possible for the deflection impulse to alter the NEO's trajectory away from the its original Earth-impacting trajectory. In other words, the magnitude of the required deflection change in velocity becomes smaller as the time of the deflection (D) increases. However, the relationship

between the time of deflection (D) and the Earth miss distance is often not straightforward. It is generally not a simple linear relationship.

Ready to give it a try? Here is the general approach to follow for the Delta-V Mode:

1. Select the “Delta-V” tab in the Main Panel if it is not already selected.
2. Select the Object from the pull-down list of simulated impacting asteroids.
3. Also in the Main Panel, select the time of deflection (D). You can input this or use the increment/decrement buttons.
4. As D changes, the yellow dotted line moves to the new time in the Plot Panel, and the Earth and asteroid positions adjust to their new positions in the Orbit Panel. It is also possible to select D by pointing and clicking in the Plot Panel, which allows for even finer control when a plot is zoomed in.
5. It is also useful to call up the Orbital Parameters pop-up box, by clicking Orbital Parameters in the Main Panel. These parameters change as you change D, especially the True Anomaly, which indicates the object’s position at the time of deflection relative to the perihelion point. True anomaly is near zero or 360 degrees when the asteroid is near perihelion.
6. Deflections are usually most effective when the asteroid is near its perihelion point. For each D, note how close the object is to its perihelion point. You can do this by eye on the Orbit Panel 3, or by the proximity of D to a local minimum when the Sun-Object distance is selected in the Plot Panel, or by how close the True Anomaly is to zero in the Orbital Parameters pop-up box in the Main Panel.
7. Select the size of the deflection you wish to apply in each component (along track, cross track and normal): ΔVA, ΔVC and ΔVN. You can accomplish this using the sliders, but it is often more instructive to use the increment/decrement buttons that usually work in smaller increments. (You can set the size of these increments by clicking the “Slider Δ’s” button on the Main Panel.)
8. As you change the ΔV components, both the total magnitude of the ΔV and the perigee distance of the deflected orbit are updated in the Values Panel, and the position of the trajectory point in the B-Plane Panel, is updated. (The green dot is the current trajectory, blue dots are for previous trajectories, and the red dot is for the undeflected trajectory.) Did your deflection attempt succeed in moving the trajectory point a safe distance outside the Earth’s capture radius (the red circle)? If not, try different values for the ΔV components until you obtain a successful deflection.

9. Try each ΔV component independently, leaving the other components at zero, and note the differences in effectiveness of the components. Usually, a successful deflection can be achieved with much smaller ΔV values in the along-track component than in the others.
10. Deflections usually move the asteroid along the ζ-direction in the B-Plane, which corresponds more closely to the asteroid's along-track direction at the potential Earth impact point.
11. To reset the ΔV's to zero, click "Reset" on the Main Panel; to clear the B-plane of the older blue circles, click "Clear History" at the top of that panel.

Detailed Example for Delta-V Mode:

1. In the Main Panel, select the Delta-V tab, select object SIM1, and set the time of deflection (D) to 1295 days (3.546 years) before Earth impact.
2. On the Plot Panel, note that this deflection interval (D) corresponds to a Sun-asteroid distance of about 1 au (very near its perihelion) and an Earth-asteroid distance of about 1.9 au. The Sun-asteroid and Earth-asteroid distance plots can be expanded by highlighting the specific region of the main plot you want to zoom in on. Also note that prior to the spacecraft's impact, the Earth impact point is within the Earth's red capture radius in Panel 5. In the Orbit Panel, the position of the Earth at the potential impact is noted by the black dot near the six-thirty (6:30) location on the plot, and the positions of the Earth (in blue at 1:30) and the asteroid (in red at 5:30) are given at the time of deflection (D).
3. Set the along-track deflection delta-V (ΔVA) to -10.0 mm/s, and note that the trajectory position (green dot on the B-Plane Panel) has moved from its previous (red) position to a location -1.7 Earth radii downward and well outside the capture radius of 1.299 Earth radii.
4. Hence, a deflection maneuver of -10 mm/s, which acts counter to the direction of the asteroid's in-orbit motion (along-track) some 3.546 years prior to the predicted impact, will move the asteroid off the Earth capture cross section, which is 1.299 Earth radii. The impact has been averted! Congratulations… but your job is not done! A deflection of this size and direction at your chosen deflection time D may not be achievable with current launch capabilities. In the next section (Intercept Mode), we can investigate deflection strategies, optimal deflection and launch times and see whether a viable, single launch option exists for deflecting this fictitious Earth threatening asteroid.

b) Guide to Intercept Mode:

In Intercept Mode, you deflect the asteroid by hitting it with an impactor spacecraft launched from Earth. You still choose the time of deflection D, but you have less control over the magnitude and direction of the deflection impulse. For example, you probably won't be able to achieve the optimal ΔV direction for your deflection. That direction is basically set by the trajectory of your impactor spacecraft, which in turn is determined by when you launch it. The key parameter you do have control over in this mode is the Launch Interval (L to D).

The launch interval (L to D) is the time between the spacecraft launch from Earth and the time when the spacecraft impacts the asteroid--it's basically how long the spacecraft is flying. Once you specify both D and L-to-D, the spacecraft's free-flying trajectory from Earth to the asteroid is determined. It is computed as the solution to Lambert's Problem (see Appendix A), and it fixes two important quantities of your mission: 1) the launch energy (C3) that is required for your chosen mission scenario, and 2) the relative velocity vector of the spacecraft when it impacts the asteroid, $\mathbf{V}_R$. This vector is used to compute the momentum transferred to the asteroid by the impacting spacecraft, and it fixes both the size and the direction of the ΔV. In other words, it sets ΔVA, ΔVC and ΔVN. Your deflection attempt will only be successful if the C3 required for your deflection mission scenario is available from your selected launch vehicle.

The calculation of the momentum transferred to the asteroid depends on the size and density of the asteroid (which determine its mass), as well as the momentum transfer factor called Beta (β). For the input values of D and L, the program determines the C3 value for the selected launch vehicle and then the program determines the maximum spacecraft mass that can be launched. In a realistic scenario, you would have little control over the asteroid properties and momentum multiplier, but there would be rough estimates for them. Your goal should be to see whether you could find acceptable values for D and L-to-D so that your mission will successfully deflect the asteroid away from Earth impact with a single spacecraft launch.

Finding acceptable combinations for D and L-to-D can be tricky. You may have to use a trial-and-error technique, but the following general rules of thumb should help:

- As in the Impact Mode, you generally get a bigger deflection if you set D to a time when the asteroid is near its perihelion point, and, as before, the earlier the perihelion point, the better.
- In Intercept Mode, however, you also want to maximize the launch C3 so as to maximize the possible spacecraft mass. Allowing a high spacecraft

mass depends on finding good selections for *both* D and the Time of Flight (L to D). It is often preferable to set D to a time when the asteroid is near its Line of Nodes. The **Line of Nodes** is the line of intersection of the asteroid orbit plane with the ecliptic (the Earth's orbit plane). It is shown on the Orbit Panel as a grey-blue line drawn through the Sun from the impact point to the other side of the asteroid orbit. Since the asteroid crosses this line twice per orbit and we already know that deflections are more effective near perihelion, the crossing nearest perihelion is generally the better one for setting D.

- You can increase the B-Plane deflection by selecting D and L-to-D to allow a larger spacecraft mass. Alternatively, you can assume a smaller diameter for the asteroid, or assume a lower object density, or assume a higher momentum multiplier (β).

Ready to give this mode a try? Here is the general approach to follow for Intercept Mode:

1. Select the "Intercept Mode" tab on the Main Panel, if it is not already selected.
2. Select the Object, launch vehicle and number of launches (usually 1) as well as the time of deflection (D), as before. In ascending order of lift capability, the launch vehicles are the Atlas V 551, the Delta IV Heavy and the Falcon 9 Heavy.
3. Select the Transfer Time (L to D), which, as you will recall, is the time the spacecraft takes to fly to the asteroid (i.e., the time from launch to deflection or time of flight). As with D, you can accomplish this via manual inputs, but it is often more convenient to use the increment/decrement buttons for finer control. You can set the stepsizes for these buttons by clicking the Slider Δ's button on the Main Panel.
4. In this mode, the Plot Panel displays a second vertical dotted line highlighted in blue and denoted L to indicate the Launch time. You can drag this line to change the Transfer Time (L to D).
5. Enter the object's diameter and select a density. The asteroid's mass is automatically computed and displays near the bottom of Main Panel. The mass determination assumes the asteroid is spherical. A diameter of 1 km represents a large asteroid, 0.3 km a medium one, 0.1 km for small and 0.03 km for tiny. The success or failure of the deflection depends a lot on this input: *the larger you make the asteroid, the harder it will be to deflect!*

6. Select a value for the momentum enhancement factor β (an integer from 1 – 9). A realistic value is probably around 1.5 or 2.
7. Note the new B-Plane components in the Values Panel and the location of the deflected trajectory in the B-Plane Panel (the green dot). Did your deflection attempt succeed in moving the impact point a safe distance off the Earth's capture radius? If not, try adjusting your input values of the deflection interval and the launch to deflection interval until you have moved the impact point a safe distance off the Earth's capture radius and you have done so with only one or a few launches. Multiple launches are assumed to occur on the same day with each spacecraft arriving at the same time at the asteroid.

Detailed Example for Intercept Mode:

1. In the Main Panel, select "Intercept Mode" and select SIM1 from the pull-down list. Then select a single launch of the Atlas V 551 launch vehicle. Set the object diameter to 0.14 kilometers, object density to 1.5 g/cm^3, and object beta to 2.
2. Set D to 1970 days (this places the deflection near the asteroid's perihelion, about three orbital periods prior to the predicted Earth impact).
3. In the Plot Panel, note the Earth-object distance at deflection (~2.0 AU) and the Sun-Object distance at deflection (~1.0 AU and very near the asteroid's perihelion).
4. In the Main Panel, set the transfer time (L to D) to 560 days. If you take a look at the Deflection Map for this object, you'll see a light blue color for this combination of the deflection (D) and transfer time (L to D) intervals.
5. Note that these inputs have allowed a spacecraft mass of more than 5 metric tons and the deflection has moved the asteroid trajectory point (the green dot in the B-Plane Panel) to a distance of 7.0 Earth radii from the Earth's center, well outside the Earth's capture radius (red circle). It is desirable to move this point well outside the Earth's capture radius because, in practice, there will be some uncertainty on the size of the deflection. Note also that the phase angle of 74 degrees would allow the cameras on board the impacting spacecraft to view the partially sunlit target asteroid prior to encounter.

6. Keyholes

It often happens that an asteroid on an Earth-impacting trajectory will make a close approach to the Earth one or more orbits before it impacts. If it approaches close enough during one of these pre-impact encounters, its trajectory will be changed by the Earth's gravitational attraction during the encounter, in the same way a spacecraft's trajectory is altered when it goes through a gravity assist. We can define a B-Plane for the pre-impact close Earth approach encounter in the same way we define a B-plane for the impact encounter, but note that it is a *different* B-plane at a *different* time! If the asteroid is on an impact trajectory, it will pass through a small region called a "keyhole" in the pre-impact B-plane (BP1). A *keyhole* is defined simply as *the region in the pre-impact B-plane that leads to an impact in the final, impacting B-plane (BP0)*. Passing through a keyhole in the pre-impact B-plane implies impact just as surely as passing inside the capture cross-section region implies impact in the final B-plane -- the keyhole is just defined in an earlier B-plane. Keyholes are usually small narrow regions, and usually located well away from the origin in these B-Planes.

The most important characteristic of a keyhole is its small size, much smaller than the capture cross-section of the Earth in the final B-plane. A general rule is that if the asteroid you have selected happens to have a pre-impact keyhole encounter, it is usually much better to deflect it *before it goes through that encounter* because it is generally much easier to move the trajectory away from a small keyhole than it is to move the trajectory away from the much larger Earth collision cross section. We can think of the keyhole encounter as providing *deflection leverage* in the sense that the encounter amplifies a small deflection (out of the keyhole) into a much larger deflection (off of the Earth collision cross section).

Example showing the deflection advantage provided by a keyhole:

1. In the Main Panel, select the Delta-V Mode and select Object SIM1 again.
2. On the Earth-to-Object Distance Plot in the Plot Panel, note that this asteroid has a close approach 9 years before impact, at a distance of only 0.004 au. Such a close encounter will create a keyhole.
3. Set the time of deflection (D) to 3915 days (10.719 years), which precedes the keyhole encounter by almost a full orbit, and is near the perihelion point.
4. After clicking the Reset button at the bottom of Main Panel, set the along-track deflection delta-V (ΔVA) to 0.1 mm/s. This can be accomplished either by entering this value into the textbox and then clicking outside the box, or by using the increment button.
5. Note that the trajectory position on the B-Plane Panel (the green dot) has moved to a location -1.7 Earth radii downward, outside the capture

radius of 1.299 Earth radii. You have saved the Earth from an asteroid impact once again, using a very small delta-V with the aid of a keyhole!

6. By clicking on BP1 at the top of the B-Plane Panel, note that the keyhole, nine years prior to the nominal impact, is located at about 89 Earth radii (ζ = +89 Earth radii). Note also that the green dot of the deflected trajectory has moved up and out of the keyhole defined by the two parallel red lines.
7. The effect of the keyhole becomes clear when you compare with the earlier example: when D was set to 3.546 years, a much larger ΔVA of -10 mm/s was required to deflect the asteroid a similar distance in the B-Plane. It's true that this is not quite a fair comparison because earlier deflections usually require smaller ΔV magnitudes, but even if the time D was set at two orbits earlier, at 7.146 years, a deflection of a similar distance in the B-Plane would require a ΔVA of -5.0 mm/s, still 50 times larger in magnitude than the ΔVA required before the keyhole encounter. Thus, the keyhole provides deflection leverage of about a factor of 50.
8. Also note that the sign of ΔVA required to move the trajectory downwards in the B-Plane has flipped. That's another characteristic of a keyhole: it reverses the relative direction of a deflection. The same deflection that would move the asteroid farther ahead in its orbit before the keyhole will move the asteroid farther behind in its orbit after the keyhole.

7. Caveats

It must be emphasized that this application makes many simplifying assumptions and approximations that would not be made in designing actual intercept missions. As a result, it should only be used for educational purposes. For example, in Intercept Mode, the trajectory of the impactor spacecraft is computed as the solution of Lambert's problem, which assumes the spacecraft follows a Keplerian (purely elliptical) orbit about the Sun. More sophisticated trajectories that use, for example, mid-course delta-V maneuvers, gravity assists, or "slow-push" ion propulsion are not supported.

8. Suggested References

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Appendix A – Lambert's Problem

Lambert's problem is one of the most significant and extensively studied problems in astrodynamics. Given two points (Earth at launch and the near-Earth object at impact) relative to a point mass gravitating body (the Sun) and the time of flight, a Lambert algorithm computes all possible Keplerian transfer trajectories (i.e., conic orbits) between these two points. The problem was first introduced by Lambert in 1761 and subsequently extended by Gauss.

If we are given the interval (Δt = TOF =L) between the time of launch (t_1) and the time of deflection (t_f) and the two heliocentric vectors to the positions of the launch point and the deflection point, then Lambert's problem is to find the trajectory joining them. This trajectory is determined once we find the heliocentric velocity vector at the launch point, because the position vector at that point is already given, and knowing position and velocity vectors at a given time (t_1) uniquely define the spacecraft's transfer orbit.

Figure A.1 is a notional depiction of Lambert's problem for the transfer of the kinetic impactor (KI) spacecraft from Earth to the NEO intercept at time t_f with heliocentric velocity V_{KI}. The time of flight, or transfer time, is then $\Delta t = t_f - t_1$, and the relative velocity between the kinetic impactor (KI) spacecraft and the NEO at the time of intercept is $V_R = V_{KI} - V_{NEO}$.

Solving Lambert's problem provides an initial velocity vector with respect to the sun for the transfer trajectory from Earth to another celestial object such as a NEO. This is the heliocentric velocity of the spacecraft relative to the Sun. However, we need to compute the velocity relative to the Earth in order to calculate the launch energy required. Using the Patched Conic method, a hyperbolic trajectory is assumed within the Earth's sphere of influence that must meet or be 'patched' to the transfer trajectory from Earth to the NEO. One of the velocities calculated with the Patched Conic method is the hyperbolic escape velocity. The hyperbolic escape velocity, V_{out}, is the vector difference of the velocity of the Earth with respect to the Sun, V_E, and the velocity required on the heliocentric transfer trajectory V_1 so that $V_{out} = V_E - V_1$ (see Fig. A.1). This hyperbolic excess velocity is directly related to the energy required from the launch vehicle and the launch window is then the interval over which the launch vehicle is capable of providing sufficient energy.

The launch energy per unit mass is the square of the hyperbolic escape velocity and called the C3 value, $C3 = (V_{out})^2$. The C3 required to accomplish the mission must be delivered by the launch vehicle. Each launch vehicle has a maximum C3 energy that it can deliver for a given payload mass. A successful mission requires that the launch vehicle C3 capability must be greater than the C3 required to accomplish the mission. Otherwise, the required deflection might require multiple launches with multiple impactor spacecraft.

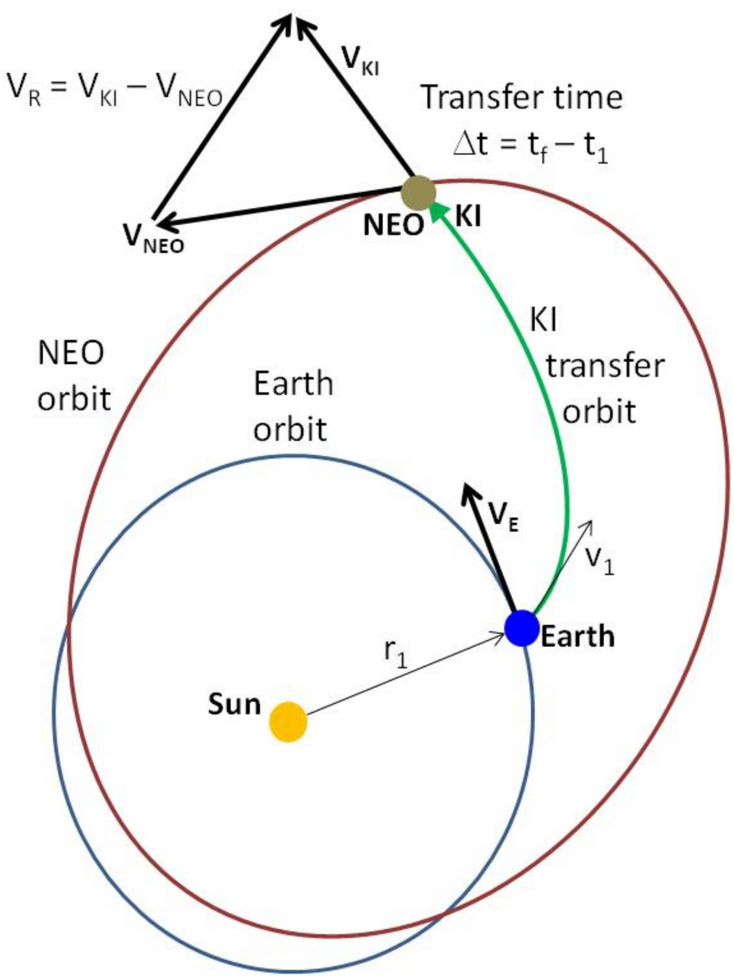


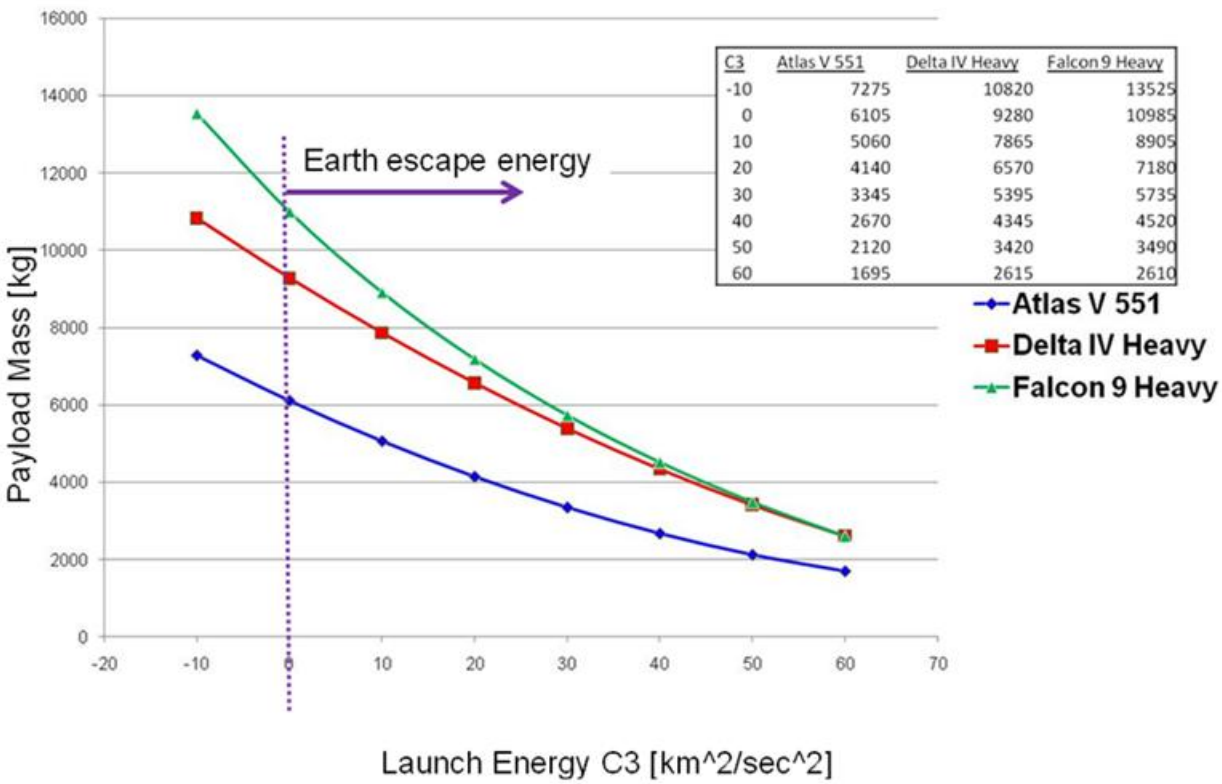
Figure A.1 Lambert's problem for the transfer of the kinetic impactor from Earth to the NEO

In addition to the required launch energy C3, the solution of Lambert's problem also provides the heliocentric arrival velocity of the kinetic impactor spacecraft at the NEO, V_{KI}. This allows the computation of the relative velocity between the NEO and the kinetic impactor, $V_R = V_{KI} - V_{NEO}$. Figure A.1 shows a notional depiction of the intercept event where V_R is the velocity at which the spacecraft rams into the NEO and transfers momentum to the object, deflecting its trajectory.

Figure A.1 shows the arrival geometry of the impactor at the NEO. The relative velocity vector ($V_R = V_{KI} - V_{NEO}$) represents the direction of impact on the NEO by the impactor. The momentum transferred to the NEO is largely in this direction and the component in the along-track direction (A) changes the NEO's orbital energy or semi-major axis. The Lambert arc dictates the direction of the impulse applied to the NEO. If the impactor is going slower than the NEO in the along-track direction then the impactor must get in front of the NEO so that the NEO will catch up to it and collide with the impactor. This will decrease the NEO's orbital energy and period. Conversely, if the impactor is going faster than the NEO in the along-track direction then it must approach the NEO from behind and slam into it thus increasing the NEO's orbital energy and period. Allowing an increased spacecraft mass or increasing the momentum multiplier beta will proportionally increase this impulsive ΔV while increasing the NEO's diameter or density will decrease the ΔV.

Appendix B – Launch Vehicle Lift Capabilities

NEO deflection missions follow interplanetary trajectories, requiring Earth-escape performance capability from the launch vehicle. Performance information on launch energy capabilities, called C3, is published by the launch vehicle contractors in the user's guides for these vehicles. The data are contained in performance plots similar to Fig. B.1, which are available from the Launch Services Program performance web site hosted by the Flight Dynamics Branch at the Kennedy Space Center. The Atlas V 551, Delta-IV Heavy and Falcon Heavy performance data provided by the Launch Services Program were integrated into this web tool and are used to determine whether or not the spacecraft can be launched onto the required trajectory to deflect the NEO.



C3	Atlas V 551	Delta IV Heavy	Falcon 9 Heavy
-10	7275	10820	13525
0	6105	9280	10985
10	5060	7865	8905
20	4140	6570	7180
30	3345	5395	5735
40	2670	4345	4520
50	2120	3420	3490
60	1695	2615	2610

Figure B.1 Performance curves for current and envisioned launch vehicles