Deflection of an Incoming Asteroid Strike

CREST Project Specification

Dr Michael McEllin September 2021

Motivation

Astronomers have identified a near-Earth asteroid in a potentially dangerous orbit. There is a non-negligible probability that it may strike the Earth in the foreseeable future - though it is known that the orbit will not intersect Earth's orbit for at least two decades (and further refinement of the orbit after more intensive observations may indeed push the point of maximum risk back by one or two decades).

Initial observations suggest that the asteroid is uncomfortably large, probably at least 300m in diameter (capable of devastating a country the size of the UK in a direct strike) but perhaps as large as 1000m (capable of causing continent wide damage).

You are part of a team that is charged with preparing an orbit-deflection plan, taking account of the fact that different (and less difficult) approaches may be possible with longer lead times (say 40 years) and smaller asteroids. If, on the other hand, the lead time turns out to be short and the asteroid larger than hoped, more aggressive methods may be required (perhaps using nuclear explosions).

You are now required to do some *scoping calculations* of possible alternative ways to handle the problem. This is very common at the early stages of a project: we look at a number of alternatives and see which is likely to be the most promising strategy, before investing a lot of time doing very detailed and complex planning on the selected option.

Background Science

The Solar System contains many minor bodies, generally called *asteroids* if they are observed by astronomers to be in fairly regular (nearly circular) orbits, or *comets* if they are in very eccentric elliptical orbits. (The are agreed stricter terminologies amongst professionals, but our informal definitions will be sufficient for our purposes.)

We dismiss comets from our current consideration. They are much less numerous than asteroids (perhaps only 5% of the potential hazard) and very much more difficult to observe in time to plan deflections and then much harder to deflect because they are usually moving much faster and would need a much bigger push to achieve a sufficient change in the orbit. Most comets originate in a very large shell of icy bodies outside the orbit of Neptune that left over from the origin of the Solar System. Gravitational interactions with Neptune (or sometimes even a nearby star) occasionally deflect their orbits into a game of gravitational pin-ball with the gas giants and the inner planets.

Most asteroids appear to originate in the asteroid belt between Mars and Jupiter. There are many hundreds of thousands of object larger than 100m or so in diameter. From time to time (through a fairly complex process) the gravitational field of Jupiter starts to nudge the orbit of an asteroid that is in the wrong place at the wrong time, and gradually turns it from a nice regular circular orbit to one that is increasingly elliptical which means that eventually its orbit intersect that of the inner planets. The eventual fate of such asteroids is collision with the inner planets or more likely the Sun. The surface of the Moon shows that collisions used to be much more frequent in the distant past, but there are hundreds of know impact craters on the Earth. (Geology mostly erases the signs, so what we see today is generally those from the last hundred million years or so.) Notoriously, a 6-10km asteroid wiped out the dinosaurs 60 million years ago.

At present there are known to be about 11,000 objects in orbits close to the Earth's orbit (these are known as Near Earth Objects - "NEOs" - and a smaller set of "PHOs" - potentially hazardous objects - which actually cross the Earth's orbit. Various Earth-based telescopes and satellites monitor these objects, but there are surprises from time to time, because it is often very difficult to object between us and the Sun. Furthermore, some of the asteroids are very, very black (think the blackest soot you have every seen) so they reflect only a tiny fraction - perhaps only 1% - of sunlight. They can only be detected by observations by satellites with infrared detectors because they do absorb sunlight and need to re-radiate it - but they are still very cold, only just show up against the background and we might miss the smaller ones. Fortunately, we are pretty confident that we know the locations and orbits of all the "planet killer" asteroids and orbit predictions out for several centuries show that they are not presently dangerous. Nevertheless, some of these object do come remarkable close to the Earth from time to time - even passing between the Earth and the Moon. A few years ago a 332m diameter asteroid known as 98942 Apophis[1] was giving great concern with a very close encounter possible April 13th 2029 and another in 2036 (it is likely to pass underneath our geosynchronous satellites). Fortunately very intensive orbit observations have reduce the orbit uncertainties and confirmed that we are now safe for at least 100 years - but it is a very close thing[2]!

In order for there to be a collision between an asteroid and the Earth they need to be at the same place at the same time. Therefore we can avoid a collision either by moving the orbit of the asteroid (changing its shape) so that it misses the Earth or we can delay (or speed-up) the asteroid so that it misses its rendezvous. The different amounts to pushing the asteroid on the side to change the orbit shape or pushing on the front or back to slow it down or speed it up.

We also have a choice between using a gentle push over a long period or a very hard push (perhaps and explosion) over a short period. It should obvious that the longer the lead time the easier we will find the task. (For example, a small change in velocity adds up to quite a big different in distance over 40 years - and one Earth diameter is enough to produce a miss.) Furthermore, we do not want to make things worse with our efforts: for example avoiding a 5% collision chance in 2036, but making it certain in 2039. There is a distinct advantage in the "gentle push" methods because we can monitor the effect of our actions and adjust as necessary. It has been calculated that for an asteroid that is not too large, and where the impact time is several decades away, even paining one side of the white - increasing the rather slight effect of pressure from solar radiation - may well be sufficient. Most likely one would be considering the use of low-thrust high-efficiency rock motors (e.g. "ion drives") that are used for positioning communication satellites. They can run for many years continuously.

Let us scotch now one scenario that has appeared in blockbuster feature films. Using a nuclear explosion to destroy the asteroid is *not* likely to be a viable scenario. It would take a vast amount of energy to vaporise an asteroid - it is quite unfeasible (though you might like to calculate it for interest). Even fragmenting an asteroid takes substantial amounts of energy and it may not help: you end up with a collection of fragments mostly moving along the same orbit and they may well cause the same amount of ground damage. (In some calculations it turns out to be worse than being hit by a single body.)

The aim of using nuclear explosions to deflect the orbit of an asteroid is to evaporate part of the surface, which expands away into space generating a reaction thrust on the asteroid. You may need to consider whether we would be able to calculate the effect of such an event with sufficient accuracy.

---

[1] A point of terminology: all know asteroids have numbers, which is formally their unique identifier. Some (usually larger ones) have names - e.g. "Apophis". The number should always be used at least once when describing these objects, so *99942 Apophis* is the full formal name, whereas *Apophis* on its own is strictly not a sufficient identifier. Informally, we tend not to be so picky unless we are writing for the professional literature.

[2] Furthermore, a spacecraft is currently on its way to rendezvous with Apophis to find out about its composition - which affects how you might want to deflect it if necessary.

BACKGROUND READING

You may find the following documents a useful introductory read.

- This report is worth looking at for non-technical introductory reading, but bear in mind that it is now a couple of decades old and a good deal has changed (particularly the available instrumentation and knowledge of the NEO population).
  - **A Report of the Task Force on Potentially Hazardous Near Earth Objects**. Available as a PDF download at https://space.nss.org/wp-content/uploads/2000-Report-Of-The-Task-Force-On-Potentially-Hazardous-Near-Earth-Objects-UK.pdf .

- NASA is charged by the US government with the responsibility for monitoring potentially hazardous asteroid and they even used to have an employee with the job title "Planetary Defence Officer" which must have been a really cool job title to have. They keep a useful website about Near Earth Objects at *https://cneos.jpl.nasa.gov*.

- The *Association of Space Explorers* have produced a useful document which can be easily found on the web: Schweickart, R.L., T.D. Jones, F. von der Dunk, S. Camacho-Lara, and Association of Space Explorers
  - **International Panel on Asteroid Threat Mitigation. 2008. Asteroid Threats: A Call for Global Response**. Association of Space Explorers, Houston, Tex at *https://www.space-explorers.org/resources/Pictures/photos/ATACGR.pdf* .

- This longer and more technical document from the USA's National Research Council can be downloaded free, if you fill in a short form:
  - **Defending Planet Earth.** See *https://www.nap.edu/catalog/12842/defending-planet-earth-near-earth-object-surveys-and-hazard-mitigation* .

- NASA has a Planetary Defence Office[3] - see https://www.nasa.gov/planetarydefense/ with useful information on its web site.

A Note on Terminology

Engineers and scientists who work on things like this have a conventional and precise terminology that may different somewhat from the common usage amongst the public.

Hazard: something that is *potentially* dangerous (but only if something that goes wrong). For example, the petrol tank of a car is a hazard because it can cause a serious fire if damaged in a collision. Hence, we take steps to avoid hazards becoming dangers. Hazards are all around us all the time but mostly do not become dangerous.

Danger: a clear and present threat to life.

Risk: the combination of the chance of some undesirable event occurring and the consequences of that event. The risk of a planet killer asteroid impact is low because although the consequences of the event is very high the probability is very low. Similarly, the risk from pebble sized meteorites is very low because although the probability of them hitting the Earth is high (many per day) the have minimal consequences. There are higher risks from, say, 20-30—meter sized objects which hit the earth every 50-100 years, but potentially can cause serious local damage (as at Chelyabink in 2013 when about 1500 people were injured by flying glass when a previous undetected 20 meter (or so) object exploded in the atmosphere). We often need to use some numerical measure for comparing risk, such as the product of the number of lives lost and the probability of the event. There are other methods of comparing risk. The ***Torino*** scale is often used when discussing asteroid impacts.

---

[3] The head of this Office gets to call himself "*Planetary Defence Officer*" - how cool is that!

What you Need to Do

You have been informed of an NEO with a diameter between 100 and 500m that has a high chance (say more than 10%) of impacting the Earth in 40 years.

At present, therefore, you do not know the mass of this object. You will have to consider a range of scenarios.
- In fact, some asteroids may be fairly solid and dense rock (density perhaps 4kg/ltr, other seem to be “rubble pile” jumbles of rock with lots of internal voids and if they are mainly ice the density may be only 2kg/ltr or even lower.

In general, in situations like this we assume the worst to start with, and hope the future observations may make our problem easier than we thought. (We do not want to be in a situation where all our plans turn out to be ineffective because they are based on assumptions that are too optimistic. Being too pessimistic, however, can also be a problem because we might be tempted to take unnecessary risks, or use too many resources that are better deployed in a different way. Safety engineering usually has to balance cost and risk. If you underestimate the risk there is a heavy cost in lives. On the other hand, if you overestimate the risk and avoid the problem by miles, all the public have to complain about is the cost.)

The Earth’s orbit is very nearly circular, and we might as well assume that it is circular. (It will not essentially change the science we need to consider.) On the other hand we will assume that our hazardous asteroid has a slightly elliptical orbit which has a *perihelion* (its close approach to the Sun) 10% closer than the Earth and its *aphelion* (the furthest distance) 10% further away. We will assume that the plane of the orbit is the same as that of the Earth, which maximises the chance of an encounter.
- From this information you should be able to calculate the speed of the Earth in its orbit and therefore the amount of time the Earth takes to cross the track of the asteroid on each orbit.
- You either have to delay the asteroid by this amount of time OR move the orbit horizontally by the diameter of the Earth to avoid a collision at the critical point.
- Neither or these strategies necessarily avoid encounters on future orbits, of course,: we are still crossing the Earth orbit at regular intervals, but we will leave that calculation aside for now and assume that any such encounter is sufficiently far away that we can deal with it more easily.

Uses basic mechanics (Newton’s Laws) to calculate the change of momentum (the impulse) you must apply to vary the asteroid velocity sufficiently to delay its arrival if you have, say 10, 20, 30 or 40 years of warning time. You will, of course, need to produce a table for the range of possible asteroid masses.

1) CALCULATE THE FORCE THAT MUST BE EXERTED OVER VARIOUS PERIODS.

What ranges of force are available from various types of rocket motor? Are they sufficient? (Look at the period over which the rocket must run to produce the required total impulse.) How does the available technology compare with the requirements?

We can tackle this problem at various levels of approximation. A professional physicist would first do a quick-and-dirty estimate. Along the following lines:
- I need to shift the asteroid by, say 12,000 meters at the end of, say X years.
- What change of velocity would this imply?
- What impulse do I need?
- What force must I apply to the front (or back) of the asteroid)?
- This result will not be quite right but it will not be wrong by, say, a factor of 10. If the answer looks reasonable (“in the right ball-park”) I will do a more sophisticated calculation without the approximations.

In reality, if we apply a force to the front of the asteroid we will change the velocity of the asteroid and this will also change the shape of the orbit, which is probably all to the good. You have sufficient knowledge, with A-Level physics and maths, of Newton’s Laws and his theory or orbits to estimate what will happen if you apply a short impulse at perihelion or aphelion. (This is where the calculations are easiest.) It is a bit harder to do the calculation when the force is applied at any other point in the orbit (not impossible but you might get lost in algebra) and the answer would almost certainly be somewhere between the effect at aphelion and perihelion. This second level of approximation will probably be more than sufficient. (This is the way physicists work in the real World: chip away at the problem from different sides by solving easier but related problems.[4])

If we still look like we have a viable plan we would then probably hit the problem with a full computer calculation using one of NASA's orbital mechanics programs, but this is out of scope for the current project.

Things look a bit more complicated if you are investigating what may happen when you apply a continuous gentle force over many orbits. This, however, is not as difficult as you might at first imagine: we just switch to thinking about energy rather than momentum.

Think about a circular orbit first (the elliptical case is almost the same). The energy in the orbit consists of potential and kinetic energy. If we add energy (by pushing continuously and gently from behind) we will clearly create a spiral rather than a circular orbit, but each orbit is almost circular, so we know how to calculate its energy. Hence, all we need to do is work out how much energy we give on each circuit round the orbit and work out the corresponding radius. The reverse applies if we push backwards from the front of the asteroid. This is, of course, another approximation, but it will be pretty good if the force is sufficiently gentle.

We can assume that with an originally elliptical orbit, it will just increase or decrease in size while keeping the same shape (the same eccentricity).

2) EXAMINE AVAILABLE TECHNOLOGIES

A number of thrust technologies are now available for spacecraft. These include:

- Chemical rockets
- Ion rockets
- Plasma thrusters
- Nuclear (nuclear rocket propulsion, or nuclear explosion).
- Solar sails (very low thrust but free fuel).

What are their relative advantages and disadvantages in this context?

Do we have the navigation technology to position spacecraft as required?

Can we fix rocket motors to asteroids?

Can we monitor the position of an asteroid under thrust with sufficient accuracy to be sure we do not cause more problems than we solve?

How long does it take to organise a space mission using novel technology?

---

[4] If you think you may be aiming for a science or engineering career I would strongly recommend a book that is available free on the Internet: ***The Art of Insight in Science and Engineering*** *https://mitpress.mit.edu/books/art-insight-science-and-engineering* . You will find a link on this page that allows you do download a copyright legal PDF. This is how real physicists and engineers start solving difficult problems.