Near-Earth Object Avoidance Mitigation: Profiting One Rock at a Time

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Abstract. Several Near Earth Object (NEO) avoidance mitigation concepts have been investigated. A simplified metrical analysis methodology is presented to demonstrate the viability and added benefits of methods. In particular an associated cost/additional benefits analysis (benefits beyond Earth protection) is presented. Nuclear weapons remain the clear method of choice to deflect a NEO, but it has little economic value beyond that. Other NEO avoidance mitigation methods offer potentially greater economic return and may warrant development. More research is required to create objective, measurable criteria for each NEO avoidance method. Saving the Earth one rock at a time might be profitable.

1. Introduction
Sixty-six million years ago a 10 km wide asteroid struck the Earth causing a massive extinction event, wiping out the dinosaurs and ultimately allowing humanity to rise from the ashes some 200,000 years ago [1]. Asteroids continue to strike the Earth today. Below are graphs, taken from Nelson [2], of the frequency of asteroid strikes versus diameter (figure 1) and energy (figure 2) to emphasise the impact of potential asteroid collisions.

As of 23 March 2016 the National Aeronautics and Space Administration (NASA) reports that there are 13,705 Near Earth Objects, or NEOs, greater than 140 m in diameter, of these 710 are larger than 1 kilometer in diameter. Any one of these can cause great damage if it struck the Earth; even smaller ones can. On 15 February 2013 a small 20-m in diameter asteroid exploded about 30 km above Chelyabinsk, Russia with the energy of 20 to 30 times more energy than that of the nuclear weapon unleashed over Hiroshima in 1945. The high altitude explosion limited damages to about $30 million or more and injured ~1,500 people. There was no reported detection before it entered the atmosphere. On Halloween and Christmas Eve 2015 a comet and an asteroid, 600 m and 1,100 m in diameter, passed uncomfortably close to Earth. Each, had they impacted, would have caused massive devastation. Worse still the Halloween comet was detected only 21 days before its nearest approach leaving Earth defenses, whatever they are, helpless to respond.

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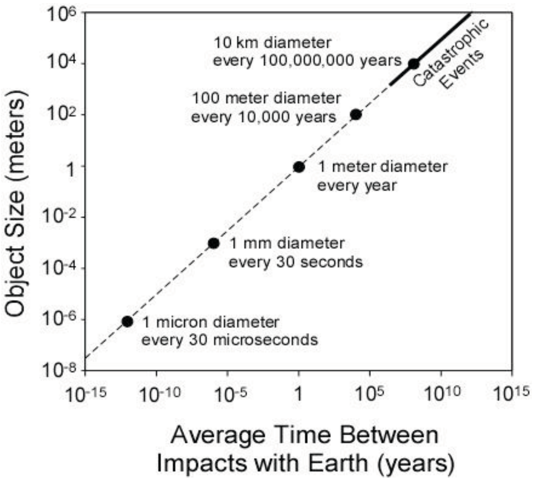

Figure 1: Average time between impacts of asteroid strikes vs diameter [2].

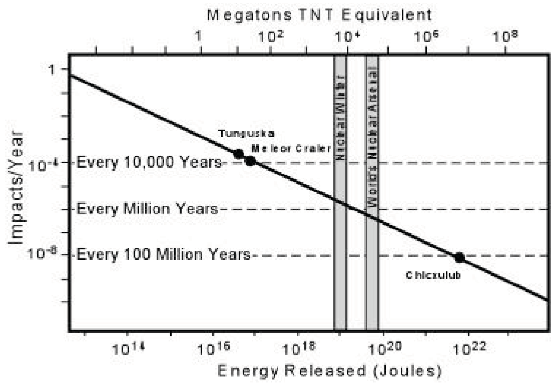

Figure 2: Impacts per year vs Energy Released [2].

What are the various methods devised to save us from a celestial encounter? Lamb [3] listed 10 possible asteroid avoidance mitigation strategies in no particular order; his 1st was the nuclear option and his 10th simply evacuate the predicted impact area. His methods for Earth protection are:

Nuclear Device (ND) - launch a nuclear device(s) to knock the NEO off course even at close range,
Kinetic Impactor (KI) - launch a weighted object to knock the NEO off course,
Solar Paint (SP) - paint a portion of the NEO white and another black and it will drift off course,
Solar Sail (SS) - attach a solar sail to the NEO and let the solar winds move it,
Solar Net (SN) - encase the NEO in a mesh net; it will act like a solar sail,
Solar Mirrors (SM) - station mirrors in orbit about the NEO and use focused sunlight to move it,
Rocket Engine (RE) - attach a rocket engine and drive it away from the Earth,
Gravity Tractor (GT) - rendezvous a large, heavy spacecraft with the NEO and use gravity to pull it,
Robotic Miners (RM) - place robotic mining equipment on NEO and expel fragments providing push,
Evacuation - evacuate the potential impact zone.

Using Wikipedia [4] another variation of the rocket engine was found: the Ion Beam shepherd (IB) gently pushes the NEO out of orbit from a small spacecraft. Only the first two options, nuclear weapons and kinetic impactors, seem plausible at this time [5]. The nuclear option is the only current technology available to deflect large NEOs [6].

There are 70 space agencies of which 13 have launch capabilities and only 3 countries are currently capable of human space flight, USA, Russia, and China [7]. Only two agencies have set up specific programmes relating to Earth Protection, they are: NASA and the European Space Agency (ESA). Such programmes are in their infancy in Russia and other countries. If nuclear weapons are the only option at present then Earth protection is left to only 7 nations with both miniaturised nuclear warheads and launch capabilities. One possibility to increase the number of organizations capable of protecting Earth is by identifying technologies with non-military applications but with alternative economic benefits. Below simplified metrics of the various NEO avoidance mitigation strategies as it relates to economics is presented.

2. Metrical Analysis of Mitigation Methods

Excluding evacuation, there are 10 possible NEO avoidance methods mentioned above. In order to compare each method a simple metric is created below where we try to answer 2 questions: "Can we build it?" and "Will it work?". A second set of metrics to compare associated costs and additional benefits of each method is also presented. Associated costs are a measure of the total costs relating to the method from development through to successful completion of mission. Additional benefits are a measure of the benefits from the development to implementation not relating to actually protecting the Earth from catastrophe, e.g. new industrial opportunities, new technologies, etc.

For each metric there are a series of questions asked, each requiring a score from 1 to 10 (from bad to good, hard to easy, etc.). In table 1 the metrics, groups of questions, and how they are scored are presented. Note that this list is by no means complete or demonstrative of the topics but serves as a starting point for further development.

Table 1: List of questions asked for each metric and how each are scored.

"Can we do it?"		
C1	Does the tech exist?	1=none, 10=all
C2	How mature is the tech?	1=new, 10=mature
C3	How easy is it to prepare?	1=hard, 10=easy
C4	Time to develop?	1=long, 10=none
C5	Do resources exist to do it?	1=none, 10=all
"Will it work?"		
W1	How long will it take to succeed?	1=decades, 10=hours
W2	Will it be effective?	1=no, 10=completely
W3	Are there risks to failure?	1=significant, 10=none
W4	Is it proven tech?	1=no, 10=completely
Associated Costs		
AC1	Development costs	1=high, 10=low
AC2	Capital expenses	1=high, 10=low
AC3	Operational costs	1=high, 10=low
AC4	Maintenance costs	1=high, 10=low
AC5	Impact of economies of scale	1=high, 10=low
Additional Benefits		
AB1	Is it prestigious?	1=low, 10=high
AB2	Is there human capital development involved?	1=low, 10=high
AB3	Are there alternative economic uses?	1=low, 10=high
AB4	Are there technology spinoffs?	1=low, 10=high
AB5	Are there opportunities for private investment?	1=low, 10=high

For metrics representing "Can we do it?" and "Will it work?" a simple average is calculated. Economies of scale decrease the costs of capital, operations, and maintenance, and hence it is accorded greater weight. Likewise development costs are inherently expensive up-front costs and also afforded a greater weight. The score for associated costs is determined by

$$\text{Score} = (\text{AC1} + \{[(\text{AC2} + \text{AC3} + \text{AC4}) / 3] + \text{AC5}\} / 2) / 2. \tag{1}$$

Likewise if there are opportunities for private funding the weighted benefits are increased; it is naively accorded equal weight to the sum of the others. As with the metrics used, these weights and the relationships of each, have to be better determined. The score is calculated using

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Score = [(AB1 + AB2 + AB3 + AB4) / 4 + AB5] / 2. (2)

The scores listed in tables 2 & 3 are guestimates based on present technology, future planning and present business practices. They should not be seen as exact in any way and are used merely for presentation purposes; they are best guestimates by the author.

Table 2: Score for each avoidance mitigation method. Note that the two-letter initials of each method are used for identification.

	Can we do it?						Will it work?				
	C1	C2	C3	C4	C5	Score	W1	W2	W3	W4	Score
ND	9	9	7	7	10	**8.4**	10	9	7	8	**8.5**
KI	9	10	7	3	10	**7.8**	5	6	7	6	**6**
GT	5	3	3	3	7	**4.2**	3	4	3	3	**3.25**
SS	7	4	4	3	5	**4.6**	6	6	5	4	**5.25**
SP	7	5	3	3	7	**5**	4	4	5	2	**3.75**
SN	7	5	5	3	7	**5.4**	4	4	5	2	**3.75**
SM	7	5	6	4	7	**5.8**	6	6	6	5	**5.75**
RE	5	5	4	3	3	**4**	4	4	4	3	**3.75**
RM	5	3	4	3	6	**4.2**	3	7	3	5	**4.5**
IB	5	3	4	3	6	**4.2**	3	6	3	5	**4.25**

Table 3: Score for each avoidance mitigation method estimated for Associated Costs and Additional Benefits. Note that the two-letter initials of each method are used for identification.

	Associated Costs						Additional Benefits					
	AC1	AC2	AC3	AC4	AC5	Score	AB1	AB2	AB3	AB4	AB5	Score
ND	8	7	9	7	6	7.4	1	1	1	1	1	1
KI	8	5	6	7	2	6.0	3	3	1	3	1	1.75
GT	3	3	3	4	2	2.8	7	7	3	5	5	5.25
SS	4	4	4	4	5	4.3	5	4	3	5	5	4.625
SP	4	4	3	4	1	3.2	3	4	1	3	1	1.875
SN	4	4	5	5	3	3.9	3	4	1	3	1	1.875
SM	4	4	6	6	3	4.1	5	4	1	5	3	3.375
RE	3	3	3	3	5	3.5	7	8	4	5	8	7
RM	3	2	2	2	10	4.5	7	10	10	7	10	9.25
IB	4	3	3	3	5	4.0	5	6	4	5	5	5

Graphical representations of each set of metrics, "Can we do it?" versus "Will it work?" and "Associated Costs" versus "Additional Benefits" are presented in figure 3 and 4 respectively.

Figure 3 is divided into four areas:

- Sci-Fi – Solutions with little or no technology developed or tested.
- Not practical – Options that will demonstrate limited success.

- R&D required – Systems that can work but require significant development.
- Functional – Workable solutions with mature technologies.

Only 3 avoidance mitigation systems fall into “Functional”: solar mirrors, kinetic impactors, and nuclear weapons. Based on the scoring above the nuclear option is the best method at present. However, this has political consequences making it a difficult choice especially if these weapons are put in space for faster response time. Utilising kinetic impactors is politically more palatable but is presently only demonstratively capable of stopping small NEOs detected years before potential impact. The Double Asteroid Redirect Test (DART) mission scheduled for 2022 will study the effectiveness of the kinetic impactor method [8]. Solar mirrors are found in the Functional area of figure 3; this is suited to situations where we have significant advanced warning (years). The rest are largely in the realm of science fiction and require significant development to prove viability.

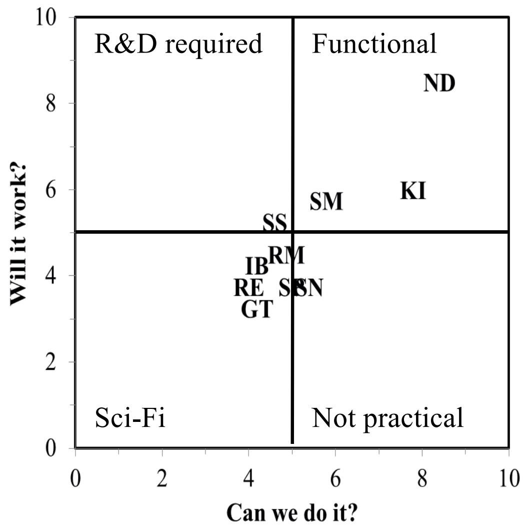

Figure 3: Metrical analysis of each mitigation system as it pertains to “Can we do it?” vs. “Will it work?”

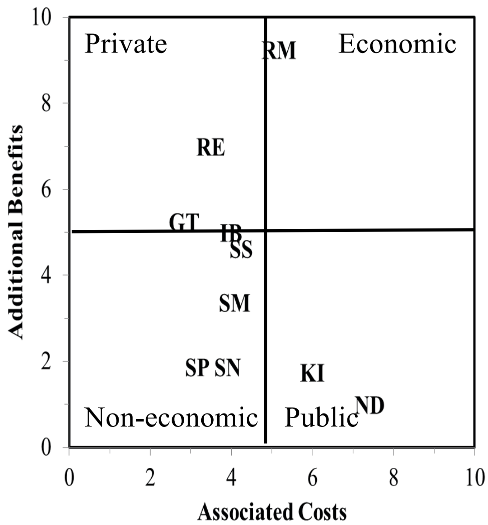

Figure 4: Cost/Benefit analysis of each mitigation system.

The Cost/benefit analysis presented in figure 4 provides insight into where funding for various asteroid avoidance mitigation systems might come, public versus private funding or a combination. Private investments flow into projects that create economic rent and a financial return to the investors. Public funding typically is used in projects for the public good, like defense where arguably there is no direct return on investment. Several of the proposed mitigation systems appear to be non-economic or expensive with little return on investment. The kinetic impactor (KI) and nuclear device (ND) options have little added benefits and would require public funding. Only robotic mining falls into the economic category; a few others (e.g. RE, GT, and IB) might be worth studying for private funding. Each appears to have economic spinoffs worth investing in.

Robotic mining (RM) is rated, in this scorecard, the best in terms of additional benefits and private investors might consider it. The weakness of RM is its associated costs; further investigation is required to determine if economies of scale, Research & Development (R&D) and decreasing space transport costs will make this an attractive investment. The American space agency (NASA) is proposing retrieving an asteroid and placing it in a lunar orbit where astronauts can practice mining it amongst other things. To give context to the potential of mining asteroids, the estimated worth of the metallic asteroid 3554 Amun (orbiting between Earth and the Sun) may be $20 Trillion dollars in precious metals [9]. It might just be very profitable saving the Earth one rock at a time!

Earth protection can be greatly enhanced if the number of organizations and people is substantially increased. Even if nuclear devices are the only answer, only a handful of countries would be capable of launching defensible measures and increasing this number is not in Earth's best interest. The survival of the human race can be increased by increasing the number of people and solutions available. In order for other NEO avoidance mitigation techniques to be developed, and increase Earth's chances of survival, alternative economic benefits may encourage development. As stated above many of the avoidance systems mentioned here have no additional benefits (benefits beyond saving the Earth). The development of rocket engines for new spacecraft offers investors significant economic return resulting from technology to be developed for new engine designs. Whereas robotic mining (RM) has significant upside economic opportunities, if instead of simply ejecting matter from the NEO, and change its course, this material is mined for valuable resources [10].

3. Conclusions

Several NEO avoidance mitigation concepts have been investigated. A simplified metrical analysis methodology is presented to determine the viability of each and if they might attract investment for non-Earth defense reasons. In particular an associated cost/additional benefit analysis (benefits beyond Earth protection) is presented. Nuclear weapons remain the clear method of choice to deflect a NEO, but it has little economic value beyond that. Other NEO avoidance mitigation methods offer potentially greater economic return, e.g. robotic mining, and may warrant private investor development. More research is required to create objective, measurable criteria for each NEO avoidance mitigation method. Saving the Earth one rock at a time might be profitable.

4. Acknowledgements

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