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On the influence of impact effect modelling for global asteroid impact risk distribution

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ABSTRACT

The collision of an asteroid with Earth can potentially have significant consequences for the human population. The European and United States space agencies (ESA and NASA) maintain asteroid hazard lists that contain all known asteroids with a non-zero chance of colliding with the Earth in the future. Some software tools exist that are, either, capable of calculating the impact points of those asteroids, or that can estimate the impact effects of a given impact incident. However, no single tool is available that combines both aspects and enables a comprehensive risk analysis. The question is, thus, whether tools that can calculate impact *location* may be used to obtain a qualitative understanding of the asteroid impact *risk* distribution. To answer this question, two impact risk distributions that control for impact effect modelling were generated and compared. The Asteroid Risk Mitigation Optimisation and Research (ARMOR) tool, in conjunction with the freely available software OrbFit, was used to project the impact probabilities of listed asteroids with a minimum diameter of 30 m onto the surface of the Earth representing a random sample (15% of all objects) of the hazard list. The resulting 261 impact corridors were visualised on a global map. Furthermore, the impact corridors were combined with Earth population data to estimate the “simplified” risk (without impact effects) and “advanced” risk (with impact effects) associated with the direct asteroid impacts that each nation faces from present to 2100 based on this sample. The relationship between risk and population size was examined for the 40 most populous countries and it was apparent that population size is a good proxy for relative risk. The advanced and simplified risk distributions were compared and the alteration of the results based on the introduction of physical impact effects was discussed. Population remained a valid proxy for relative impact risk, but the inclusion of impact effects resulted in significantly different risks, especially when considered at the national level. Therefore, consideration of physical impact effects is essential in estimating the risk to specific nations of the asteroid threat.

1. Introduction

Earth has collided with asteroids since it was an embryo planet and this process continues today, albeit at a lower rate [1]. Asteroid impacts have been responsible for at least two major disruptions in the evolution of life [2,3] and today, they remain a potential hazard for the human population [4,5]. Surveys scan the sky for asteroids in an effort to discover as many as possible and to calculate their orbits [6]. Based on the propagation of orbits, those asteroids that may potentially impact the Earth in the future are identified. The European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA), perform such collision detection using automated systems and the results are published on their respective Near Earth Object (NEO) webpages [7,8]. The NEO webpages provide information about the orbit, physical properties and impact probability of the listed objects. However, a risk assessment, involving the asteroid's possible impact locations, is not part of the available information. Only in rare cases, such as for asteroid Apophis [9], are impact locations (in the shape of an impact corridor) calculated. Impact locations can help to develop an intuitive understanding of the specific impact risk as it shows the areas that would be affected, but, to gain a reliable

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understanding for risk, impact effects and their implications for population have to be calculated at the impact locations. The calculation of impact effects has been treated in the literature, and two software tools exist that are capable of estimating impact [10,11]. Although these tools calculate impact effects, they do not routinely close the loop between orbital characteristics that determine impact conditions, probability and location, and, thus, only offer limited utility in understanding impact risk. A comprehensive risk assessment, taking into account the physical impact effects that are governed by the asteroid's speed, impact angle and physical properties on one hand and the distribution of population along the impact corridor on the other hand, is, thus far, not available. Nevertheless, such a risk assessment is needed to help determine the political and technological response when an asteroid with a significant impact probability is discovered [12]. Could existing tools be used to perform such impact risk assessment?

Given that the practice of impact location calculation is already available to some entities within the planetary defence community [13,14], it is of interest to know how well this knowledge of impact locations enables impact risk estimation. The validity of an impact risk estimate that is based on impact location knowledge alone can be gauged through comparison with a similar risk estimate that takes impact effect modelling into account. Following this logic, two risk distributions are needed: a "simplified" one that considers impact location without impact effects and an "advanced" one that accounts for impact location as well as impact effects. To generate a global distribution of asteroid impacts, a sufficiently large set of orbital and physical data of, ideally, real asteroids should be used. Using real asteroid data not only allows calculation of impact locations but also facilitates determination of representative impact conditions such as impact energy and angle. Some variable that is exposed to the asteroid impact hazard needs to be identified to complete the risk estimation process, and the global, human population map represents a suitable dataset that is also publicly available [15].

To meet the objectives mentioned above, the Asteroid Risk Mitigation Optimisation and Research (ARMOR) tool was developed. ARMOR calculates the impact locations of asteroids and presents this information in the form of spatial impact probability distributions on the Earth map. Furthermore, the physical conditions of the impact, such as speed and impact angle are determined and facilitate calculation of physical impact effects and interaction with the population on the ground. Taking into account the global impact probability, this information enables risk calculation of asteroids.

2. Method

This section describes the method of calculating impact locations and their associated impact probabilities, the resulting impact effects and how these components are used to estimate risk.

It should be noted that the term "impact" can refer to a general collision between an asteroid and the Earth, an airburst or the event of contact between the asteroid and the surface of the Earth. Where the context requires clarification, the first case is referred to as "collision" the second as "airburst" and the third case as "ground impact". The method starts with the calculation of the impact location of observed asteroids.

2.1. Impact location and probability

The nominal orbital solution of an asteroid is a state vector describing the asteroid's orbit and position that fit best the observations that are available for this asteroid. A covariance matrix represents the uncertainty region that is associated with the orbital solution. The uncertainty region has a weak direction, commonly referred to as the Line of Variation (LOV), along which the asteroid position is only poorly constrained and it typically stretches along the orbit of the asteroid [16]. Using the available observations and the current nominal orbital solution of an asteroid that are provided on the ESA NEO webpage, the freely available software OrbFit [17] was utilised to identify orbit solutions that lie on the LOV as well as inside the uncertainty region and that result in a future Earth impact. OrbFit samples the uncertainty region to find such impacting orbit solutions, which are called virtual impactors (VI).

The ARMOR tool was used to project the impact probability of each VI onto the surface of the Earth. ARMOR used the VI orbit solution from OrbFit as the initial condition for a ten day trajectory propagation that results in an impact. By sampling the LOV close to the original VI orbit solution, many impact points are calculated that form the centre line of the impact probability corridor on the Earth. Impact probability is assumed to be constant along the centre line (valid for low impact probabilities, such as used here), while a normal distribution with a 1-sigma value equal to the LOV width (a parameter available on the NEO webpages) represents the cross track impact probability. The impact probability distribution is scaled such that its integral is equal to the impact probability of the VI. The method of ARMOR, along with validation cases, is presented in greater detail in [18,19]. For practical purposes the term VI will describe the original impacting orbit solution [20] along with its immediate neighbouring uncertainty space that forms the impact corridor on the Earth. It should be noted that one asteroid may have multiple, dynamically separate impact solutions in the future and, thus, yield more than one VI.

The global impact distribution of 69 known asteroids resulting in 261 potential collisions with the Earth was calculated and the result is the basis for the simplified and advanced forms of risk calculation.

2.2. Impact effects

Six physical impact effects are associated with an asteroid impact and the occurrence of each effect depends on whether the asteroid frees most of its energy during atmospheric passage or upon ground impact. While passing through the atmosphere, aerodynamic friction heats the asteroid which induces surface ablation [21]. In this environment, smaller asteroids are prone to undergo rapid disintegration in an explosion-like event called an airburst [22] producing an overpressure shock wave, which prompts strong, gust-like winds, that propagate away from the airburst location. The airburst also emits thermal radiation that can burn surfaces which are impinged. Larger asteroids can pass through the atmosphere intact and produce a crater upon land impact [23]. The cratering process itself, as well as the accompanying out-throw of ejecta, account for two additional impact effects, while the ground impact-induced seismic shaking represents the last. Similarly to an airburst, the cratering event produces overpressure, wind gust and thermal radiation. Mathematical models of these impact effects are presented in [10] and ARMOR's impact effect modelling is derived directly from that source. Table 1 shows how the ARMOR implementation of the models for the impact effects replicates the results of the web based "Earth Impact Effects Programme" (EIEP) [10] for an arbitrarily selected airburst and a cratering impact. Errors between the two programmes are small suggesting correct implementation of the models and the errors can be attributed to the fact that EIEP values are only available in rounded format, to varying definitions of universal constants, and to incomplete descriptions about EIEP algorithm implementation.