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The global impact distribution of Near-Earth objects

Clemens Rumpf [a,*], Hugh G. Lewis [a], Peter M. Atkinson [b,c,d,e]

[a] University of Southampton, Faculty for Engineering and the Environment, SO171BJ Southampton, UK
[b] Lancaster University, Faculty of Science and Technology, LA14YR Lancaster, UK
[c] University of Utrecht, Faculty of Geosciences, Heidelberglaan 2, 3584CS Utrecht, The Netherlands
[d] University of Southampton, Geography and Environment, SO171BJ Southampton, UK
[e] Queen's University Belfast, School of Geography, Archaeology and Palaeoecology, BT71NN Belfast, UK

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ABSTRACT

Asteroids that could collide with the Earth are listed on the publicly available Near-Earth object (NEO) hazard web sites maintained by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The impact probability distribution of 69 potentially threatening NEOs from these lists that produce 261 dynamically distinct impact instances, or Virtual Impactors (VIs), were calculated using the Asteroid Risk Mitigation and Optimization Research (ARMOR) tool in conjunction with OrbFit. ARMOR projected the impact probability of each VI onto the surface of the Earth as a spatial probability distribution. The projection considers orbit solution accuracy and the global impact probability. The method of ARMOR is introduced and the tool is validated against two asteroid-Earth collision cases with objects 2008 TC3 and 2014 AA. In the analysis, the natural distribution of impact corridors is contrasted against the impact probability distribution to evaluate the distributions' conformity with the uniform impact distribution assumption. The distribution of impact corridors is based on the NEO population and orbital mechanics. The analysis shows that the distribution of impact corridors matches the common assumption of uniform impact distribution and the result extends the evidence base for the uniform assumption from qualitative analysis of historic impact events into the future in a quantitative way. This finding is confirmed in a parallel analysis of impact points belonging to a synthetic population of 10,006 VIs. Taking into account the impact probabilities introduced significant variation into the results and the impact probability distribution, consequently, deviates markedly from uniformity. The concept of impact probabilities is a product of the asteroid observation and orbit determination technique and, thus, represents a man-made component that is largely disconnected from natural processes. It is important to consider impact probabilities because such information represents the best estimate of where an impact might occur.

1. Introduction

An asteroid impacting the Earth is typically not amongst the concerns of people in everyday life. Nonetheless, the asteroid threat is real (Brown et al., 2002) and can have disastrous consequences. Asteroids have hit the Earth since the formation of the Solar System and this process continues today. The bolide over Chelyabinsk in February 2013 that injured more than 1500 people demonstrated this palpably (Popova et al., 2013). The scientific community and leading nations broadly recognize that the asteroid hazard is a significant threat to our civilization. A result of this recognition is the establishment of international organizations (UN Office for Outer Space Affairs, 2013) to address the threat and commencement of the search for potentially Earth-colliding objects (National Research Council, 2010). The products of the search for asteroids are publicly available Near-Earth object (NEO) webpages, which list potentially impacting asteroids, and are maintained by the European Space Agency (ESA)[1] and the National Aeronautics and Space Administration (NASA).[2] These lists include all known asteroids that have a notable chance of impacting the Earth in the next century but the impact distributions of these asteroids on the Earth's surface are not published.

* Corresponding author.
E-mail addresses: C.Rumpf@soton.ac.uk (C. Rumpf), H.G.Lewis@soton.ac.uk (H.G. Lewis), pma@lancaster.ac.uk (P.M. Atkinson).

[1] ESA NEO Coordination Centre webpage: http://neo.ssa.esa.int/.
[2] NASA Near Earth Object Program: http://neo.jpl.nasa.gov/risks/.

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Previous research has addressed the topic of the impactor distribution on the surface of the Earth, but none performed a quantitative assessment of the distribution. Three datasets that relate to the impact distribution problem and that are based on natural asteroids are known to the authors. They are based on historical impact records. The Russian "Institute of Computational Mathematics and Mathematical Geophysics" maintains the "Expert Database on Earth Impact Structures" (EDEIS) containing over 1000 impact crater features (EDEIS, 2006) and the results are available as a map that shows the locations of these impact features (confirmed and possible). However, the geological traces of impacts on Earth suffer from erosion and many might have disappeared or are not easily detected. In addition, water impacts rarely leave long-lived traces. Consequently, the data is biased towards land impacts and also depends on the localized interest of the population or scientists to identify impact features, both of which introduce additional bias into the database. Therefore, EDEIS data are not suitable for a global impact distribution analysis nor has such a quantitative assessment been undertaken. A similar dataset with the same limitations is maintained by the Planetary and Space Science Centre of the University of New Brunswick in Canada (University of New Brunswick, 2014). The third dataset is comprised of airburst recordings obtained by a global infrasound microphone network. The network's original objective was to monitor atmospheric nuclear weapons tests, but since the signature of an airbursting asteroid shares enough similarities with that of a nuclear test, the network is able to detect these natural events and triangulate the airburst location. NASA has published these data in the form of a map that is based on recordings in the 1994–2013 timeframe (NASA, 2014). These data are limited to the size regime of asteroids that experience an airburst when colliding with the Earth, but coverage is global and no bias is expected in the detection method. However, no quantitative assessment of the impact distribution based on these data has been performed; the reason might be that the data are too sparse to support such assessment.

An alternative to using observed asteroids as the basis for impact distribution analysis is to use a representative, artificial population of virtual impactors and such a synthetic population was generated by Chesley and Spahr (2004). The work focuses on the impactor distribution in a celestial, geocentric coordinate system that uses spherical coordinates with the ecliptic as reference and the Earth–Sun opposition point as origin. Notably, the work finds that most impactors approach roughly from the orbit or anti-orbit direction of the Earth with a minor concentration approaching from the opposition direction. Furthermore, it was shown that the majority of impactors are concentrated in the ecliptic plane. In contrast to the research presented here, the celestial frame does not rotate with the Earth and, thus, the locations on the Earth that the impactors would impact are not apparent, nor was this the aim of the study. In Grav et al. (2011) an impact location map of North America was shown that is based on the synthetic population, but without quantitative assessment of the impact location distribution.

In the research presented here, the future, potential impact distributions of observed asteroids were calculated and analyzed. The key motivating question was whether the impact distribution is uniform or if some regions are more likely to be hit than others. In Chesley and Spahr (2004), it was shown that impactors are expected to approach the Earth from directions that are roughly parallel to the Earth's orbit and that the majority of potential impactors reside in the ecliptic plane. In conjunction with the observation that the Earth performs a daily rotation under this constant influx, it can be asserted that all longitudinal sections of Earth are equally exposed to impacts and that the impact distribution in the longitudinal direction is uniform. However, an intuitive understanding of the latitudinal distribution of impact locations is not as easily obtained. Considering that most impactors are expected to originate from close to the ecliptic plane their impact velocity vectors should also be approximately parallel to the ecliptic plane. Further, assuming that the impactor influx density in the ecliptic normal direction is constant over the width of the Earth, the highest impact location density would be expected near the equator because the Earth surface bends away from the impactor influx towards the poles. This concept is depicted in Fig. 1. Of course, impactors do not impact the Earth on a straight line: rather, the gravitational attraction of Earth bends the impactor's trajectory towards Earth. Consequently, impactors that would miss the Earth in the absence of Earth's gravitational field actually impact because their trajectory is changed under the influence of Earth's gravity. This means that the uneven distribution on the Earth expected without gravity is attenuated somewhat towards a more even distribution because gravitationally captured impactors from outside the physical diameter of the Earth impact closer to the poles (than the equator) resulting in a more balanced near-polar impact density (Fig. 1).

To assess if the impact location distribution is uniform, the impact locations of 261 potential impactors (belonging to 69 observed asteroids), which can collide with the Earth before the year 2100, were calculated in a dynamic Solar System simulation and visualized. The considered asteroids had a diameter range of an estimated[3] 30–341 m. For comparison, the Chelyabinsk event was associated with a 19 m sized asteroid (Popova et al., 2013; Borovicka et al., 2013) while the devastating 1908 Tunguska event was likely caused by a 30 m sized object (Boslough and Crawford, 2008; Chyba et al., 1993).

2. Method

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 Line of Variation (LOV), along which the asteroid position is only poorly constrained and it typically stretches along the orbit of the asteroid (Milani et al., 2005). Using the data of available observations and the current nominal orbital solution of an asteroid that are provided on the ESA NEO webpage, the freely available software OrbFit (Milani et al., 1997) was utilized to identify orbit solutions that lie on the LOV as well as inside the uncertainty region and that result in a future Earth impact. The 69 asteroids were sampled from the ESA NEO webpage at random in the October 2014 timeframe. OrbFit samples the uncertainty region to find these impacting orbit solutions that are called virtual impactors (VI). It should be noted that one asteroid may have multiple impact possibilities in the future and thus yields more than one VI.

The Asteroid Risk Mitigation Optimization and Research (ARMOR) tool was used subsequently to project the impact probability of these VIs onto the surface of the Earth. ARMOR used the VI orbit solution from OrbFit as the initial condition for the trajectory propagation until impact. Each VI propagation was started 10 days before impact and utilized a Solar System model that considered gravitational forces from the Sun, the barycenters of the planetary systems and Pluto as well as point sources for the Earth and the Moon. The positions of the attracting bodies were retrieved from a lookup table that is based on the JPL DE430 planetary ephemer-

[3] Asteroid sizes are estimates based on their brightness and the values were taken from the ESA risk webpage.