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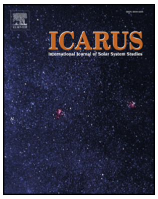

Removal of virtual impactor solutions with precovery data: The case study of 2017 XO_2

Marco Micheli[*,a,b], Juan Luis Cano[a,c], Laura Faggioli[a], Marta Ceccaroni[a], Detlef Koschny[a,d,e], Richard J. Wainscoat[f], Kenneth C. Chambers[f], Heather Flewelling[f], Mark E. Huber[f], Eugene Magnier[f], Robert Weryk[f]

[a] *ESA SSA-NEO Coordination Centre, Largo Galileo Galilei, 1, Frascati, RM 00044, Italy*
[b] *INAF - Osservatorio Astronomico di Roma, Via Frascati, 33, Monte Porzio Catone, RM 00040, Italy*
[c] *Elecnor Deimos at ESRIN, Largo Galileo Galilei, 1, Frascati, RM 00044, Italy*
[d] *ESTEC, European Space Agency, Keplerlaan 1, Noordwijk, AZ 2201, The Netherlands*
[e] *Chair of Astronautics, Technical University of Munich, Boltzmannstraße 15, Garching bei München 85748, Germany*
[f] *Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu, HI 96822, USA*

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ABSTRACT

We present a search for precovery observations of asteroid 2017 XO_2, a previously high-rated possible impactor, as an ideal example of how archival searches can be used to clarify, either directly or indirectly, the danger posed by objects whose orbits are poorly known or even lost. In particular, we explore how images which should (but do not) contain the position corresponding to an impacting orbit can provide an indirect way to exclude the impacting solution even in the case of asteroids that are currently lost and therefore not directly observable again.

1. Introduction

Since the beginning of the routine impact monitoring activities carried out by the NEODyS project at the University of Pisa and the Sentry program at JPL over the past two decades (Milani et al., 2005), a large number of newly discovered NEOs have temporarily appeared in the so called “risk lists” from these two institutions: at any given time, these lists include all asteroids (currently about 750) for which possible impacts on the Earth over the next century can not be excluded on the basis of available observations.

Typically, over the few days or weeks after such objects are discovered, new observations are acquired, often leading to the exclusion of all impact possibilities in the next century and the consequent removal of the object from these lists. In some cases, it is necessary to follow-up the object with observations over a longer period of time, using larger aperture telescopes to compensate for it becoming fainter as it recedes from Earth (Micheli et al., 2014).

There are a few cases where possible impact solutions still remain after the object becomes unobservable. Sometimes they are removed a few years later when the object is recovered with either targeted observations, or by chance rediscovery. However, in the majority of cases, the positional uncertainty of the object at the following apparition is too large to even attempt a recovery observation, and the object becomes effectively lost and unobservable[1]. When this happens, the object is poised to remain on the list indefinitely, unless additional methods to gather data become available.

This work uses a real life example to discuss how the analysis of archival data can provide the information needed to exclude the risk associated to high-uncertainty objects, even when they have become effectively unrecoverable at future apparitions.

2. The case study of 2017 XO_2

Near-Earth asteroid 2017 XO_2 was first observed on 2017 December 10 by the Pan-STARRS1 telescope (Chambers et al., 2016) on Haleakalā, Hawaii, USA, at a visual magnitude of about 22. 2017 XO_2 is an Apollo-class asteroid with an orbital period of ~ 1.2 years, and moderate eccentricity (0.36) and inclination (14.5°). Its small Minimum Orbit Intersection Distance (MOID) with our planet ($\sim 10^{-4}$au), and moderately bright absolute magnitude of ~ 22.5 make it an interesting

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* Corresponding author at: ESA SSA-NEO Coordination Centre, Largo Galileo Galilei, 1, 00044 Frascati (RM), Italy.
E-mail address: marco.micheli@esa.int (M. Micheli).

[1] As a way to quantify this statement, we point out that about half of the objects in the NEODyS risk list have an Uncertainty Parameter (https://minorplanetcenter.net/iau/info/UValue.html) $U \geq 7$, which indicates the object’s ephemeris is likely too uncertain to be recovered at the next suitable apparition.

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object in terms of possible impact threat posed to the Earth.

Despite quickly becoming fainter, enough observations had been collected within a few days after discovery to provide an initial characterization of the actual threat posed by the object during the next century: upon processing the data, both the European ESA-sponsored NEODyS system and the US NASA-supported Sentry system identified more than 100 possible future approaches with impact collision probabilities as high as $\sim 10^{-6}$.

Additional observations reported over the following week were sufficient to exclude many of the possible future impacts, but a few possibilities remained, including an approach in year 2057 that had then reached an impact probability of almost $\sim 10^{-5}$.

The next significant evolution in the object's risk assessment happened about one month later, when David Tholen reported additional observations (MPC, 2018) obtained with the Canada–France–Hawaii Telescope, which increased the observed arc from 13 to 41 days: this significant improvement in the orbit determination led to the removal of all but very few impact dates, with the vast majority of the remaining ones also dropping to probabilities of $\sim 10^{-7}$ or less. However, the particular close approach on 2057 April 28 was still compatible with the observations, and the corresponding probability of impact rose to $\sim 10^{-4}$, the highest so far for the object.

By that time, the object had already faded to approximately magnitude 24, becoming a challenging target for most follow-up facilities. This is when we decided to explore the possibility of using the repository of raw image data available from Pan-STARRS1 to achieve a better assessment of the impact threat posed by the object.

On the basis of the new orbit, it was evident that the asteroid had a promising apparition in late 2011, when it should have reached magnitude 20. A search for possible Pan-STARRS1 images in that timespan revealed a half dozen nights with suitable fields in the predicted area of the sky where 2017 XO_2 should have been located, all acquired between 2011 November 5 and 2011 December 6.

There was however an issue: the positional uncertainty of the object in that time interval, computed on the basis of just the 2017–2018 observations, was extremely large, ranging from $\pm 20'$ in early November to a peak of $\pm 1^\circ$ or more at the end of that month[2]. This large uncertainty would have implied the need to search for the object in dozens of single chips of the Pan-STARRS1 camera (each being a square of 20′) in order to cover the entire $\sim 3\sigma$ region necessary to ensure a high likelihood of success.

For this reason, in addition to attempting the complete search, we also decided to explore an alternative way of indirectly excluding the 2057 impacting solution on the basis of non-detections in the Pan-STARRS1 image archive. This approach is presented in the following section, while the actual recovery is discussed later.

2.1. The indirect removal

An innovative, alternative method to exclude the chance of a possible future impact of a now-lost object was proposed more than a decade ago by Milani et al. (2000). The idea is that, even if an object is currently lost, the subset of those orbits (from the entire range of possible orbits) which result in future impacts is actually much smaller, because of the strong constraint imposed by the need to be on a collision course with Earth at those future dates. In general, all orbits that lead to an impact would be quite similar, and they would correspond to a very small subset of the whole orbital parameter space. Therefore, at any given epoch, they “map” into a well defined small region of the sky, lying inside the much larger full uncertainty ellipse.

The idea behind this approach is simple: if this small region corresponding to impacting orbits can be thoroughly observed, and it can be conclusively proven that the asteroid is not there, then the corresponding impact solutions may be excluded, even if the asteroid itself cannot be located.

In order to test this technique for a sample case, we first focused on a set of two archival images obtained by Pan-STARRS1 on 2011 November 5.6 UT. At that time, the object was expected to be near its peak brightness of magnitude $V \sim 20.3$. The object should also have been moderately trailed in the image, since it was moving at 7.9″/min and the exposure time of the frames was 43 s. Given the sky conditions that night, and the use of the “g” filter to acquire the images (Tonry et al., 2012), we expected a SNR between 5 and 10 for each frame[3], which could be improved by a factor of $\sqrt{2}$ by stacking the two frames together.

In order to identify the exact location in the image of the position corresponding to the impacting solutions in 2057, we used two different approaches, chosen to be as independent from each other as practically possible:

- An analytical approach, starting from the orbit and covariance matrix of 2017 XO_2 provided by the NEODyS impact monitoring system.
- A fully independent approach, creating synthetic observations of the object along its sky-plane uncertainty.

2.1.1. The analytical method

In order to derive the 2057 impacting orbit, we began from the orbit and covariance information computed by the Orbit Determination software running at ESA's NEO Coordination Centre (a migrated version of the software used by NEODyS), computed from all observations in the 2017–2018 apparition. With such solution and the use of the NIRAT software (Cano et al., 2013) we sampled the covariance matrix and map it up to the encounter in 2057 in two ways. The impact plane is as defined in Valsecchi et al. (2003) and scaled with the Earth radius mapped with the impact conditions, such that a distance of 1 is a grazing pass by the Earth.

We began by making a one-dimensional, line of variations type, 3σ sampling of the covariance. This revealed a clear intersection with the Earth on the expected date of 2057 April 28, (green line in Fig. 1). The boundaries of this intersection segment (circles in Fig. 1) were used to derive initial states that could be back-propagated to the epoch of the images in 2011. Those states can be observed as the points also marked with open circles in Fig. 2.

We then noticed that the second largest eigenvalue of the orbit determination covariance was just one order of magnitude smaller than the principal one, and therefore we decided to make an additional two-dimensional elliptical sampling of the covariance to obtain a 3σ two-dimensional boundary on the Earth impact plane mapped to the time of possible impact (blue line in Fig. 1). This new mapping allowed for the determination of the 3σ boundaries of the extended impact region on the Earth (open squares in Fig. 1). In order to verify that this impact region corresponds to the actual impact region for the full covariance matrix, a Monte Carlo simulation was performed and the mapped points represented in the same impact plane, which confirmed these results. The four states delimiting the actual impact region were also back-propagated to the images in 2011 and confirmed the region derived by the synthetic observations method presented below in Section 2.1.2 (also marked with open squares in Fig. 2).

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[2] All uncertainties quoted here are intended as the semi-major axis of the 1σ level uncertainty ellipse projected onto the plane of the sky. Because of the short observed arc available for 2017 XO_2, the minor axis of the ellipse was also not negligible, being typically as wide as one arc minute.

[3] This estimate is based on the typical depth of g-band images in Pan-STARRS1, correcting for the specific seeing of the given night measured on the actual images, and compensating for the trail loss by using an effective exposure time as long as the time it took for the object to move by one seeing disk.