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AN AUTOMATED SYSTEM FOR SHORT-TERM IMPACT WARNING

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Extended Abstract—

The possibility that newly-discovered asteroids could impact the Earth within days or weeks of their first detection raises a number of challenges, from tracking and orbit estimation, to prediction and hazard assessment, and even for public communication and disaster response. Here we focus on the astrodynamics problem of identifying and analyzing potential near-term situations requiring a rapid response, both from the follow up observer community and from the orbit computing centers. Because the impact time horizon for these assessments can be measured in days, or even hours, the analysis should be concluded even before official announcement of the asteroid discovery. Such a short response time places critical demands on an impact monitoring system and requires full automation.

To date, nearly all asteroids have been discovered by ground-based optical telescopes operated by NASA-funded asteroid search programs. The usual survey strategy captures 3–5 repeat images of the same area of sky with an imaging interval of perhaps 15–30 minutes. Each imaging sequence is searched for targets that move with a roughly linear rate relative to the fixed background stars in the field. Once a target is identified, the astrometric positions are computed (usually right ascension and declination, RA-DEC) and passed to the Minor Planet Center (MPC) in Cambridge, Massachusetts. The MPC conducts a quick assessment of the likelihood that the detected object is a Near-Earth Asteroid (NEA), rather than one of the far more common main belt asteroids. If the detected object is judged to have a high enough chance of being an NEA it is placed on the MPC's Near-Earth Object Confirmation Page (NEOCP), a web page that serves to aid and encourage additional follow up observations of potentially interesting objects. The NEOCP provides telescope pointing information for follow up observers, but more importantly for our purposes it also posts all of the astrometric observations that it has received for the putative new discovery. Later the MPC officially announces the discovery once it has received enough follow up data—typically 24-48 hours of coverage—to verify the existence of the asteroid and compute an orbit. If the target is recognized as a previously cataloged asteroid at any time in this process then the data are linked to the prior discovery and published.

During this confirmation process the MPC performs some checks for the possibility of Earth impact, but these are not comprehensive and they do not compute probabilities of impact due in part to the pathologies of short-arc orbit determination. JPL's Near-Earth Object Program endeavors to provide robust impact monitoring of NEOCP targets through the implementation of the techniques outlined in this paper. This would be an important extension of the long-term monitoring already in place since 2002 with JPL's Sentry automatic system (http://neo.jpl.nasa.gov/risk).

We have so far seen two examples, about five years apart, of small asteroids discovered with ground-based telescopes about one day before impact. Remarkably, both cases were discovered by R. Kowalski operating the Mount Lemmon telescope as part of the Catalina Sky Survey. The first-ever predicted impactor, 2008 TC_3, exploded in the atmosphere above the Nubian Desert in Sudan in the early morning hours of October 7, 2008, about 20 hours after it was first detected. After discovery, the object was quickly recognized as an impactor and so was well observed prior to impact, with spectral and light curve observations informing the taxonomic type, shape, and tumbling spin state of the body before atmospheric entry. Hundreds of astrometric positions constrain the orbit of the impactor, affording a good understanding of the object's pre-impact history, as well as providing an accurate prediction for the location of the meteorite fall, which led to collection of hundreds of meteorite samples. The early recognition of the fact

that 2008 TC_3 was an impactor led to a scientific windfall that the asteroid science community would be happy to have repeated.

The second asteroid to be seen prior to impact, 2014 AA, was discovered with a similar amount of warning time between first detection and impact. However, in contrast to 2008 TC_3, the case of 2014 AA produced very little data, in part because the data processing was done on New Year's Day and the MPC staffing does not support routine manual intervention on weekends and holidays---which delayed recognition of the possibility of impact---but also because the meteorites fell into the Atlantic Ocean and so were not recoverable. As a result, we have only a handful of astrometric positions over barely an hour of time, and yet, as we shall see, these are enough to predict an impact about 21 hours after discovery. No other observations were obtained prior to atmospheric entry, which was detected by infrasound monitoring. We use 2014 AA as a working example, and show that even from the initial detections the impact was virtually certain. Figure 1 depicts the predicted impact footprint from the limited astrometry set along with the estimate of the impact location from infrasound.

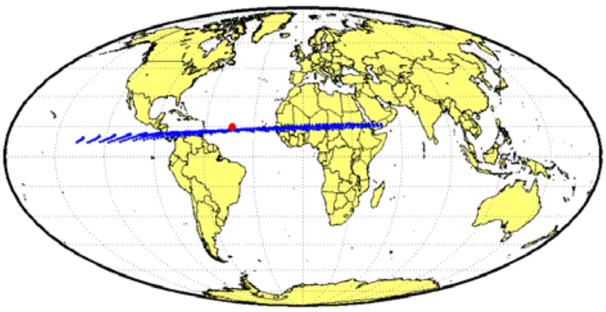

Figure 1. Predicted impact locations for 2014 AA based on the discovery observations (blue) and the CTBTO infrasound estimate (red).

The observations for such cases will often include only an hour or so of tracking, leaving severe degeneracies in the orbit estimation. We get around this problem through a technique known as systematic ranging, which explores the poorly constrained space of range and range rate to the observer, while the plane of sky position and motion is readily derived from the input observations. A raster scan in the two-dimensional range-range rate space allows us to identify regions in the space of possible orbits corresponding to collision solutions. From this scan we can understand the possible impact times and locations, and even derive coarse estimates of impact probability. To demonstrate the technique, we will review a few recent cases of interest, e.g., 2004 AS_1, 2004 FU_{162}, 2008 TC_3 and 2014 AA.

We also report on our efforts to develop and operate a fully automated short-term impact warning system that employs the systematic ranging technique. The system makes use of the latest information available from the Minor Planet Center's NEO Confirmation Page (NEOCP). Whenever an object is added to the NEOCP or the data for an existing object is updated, the hazard assessment is recomputed within minutes. All results indicating a possibility of near-term impact are immediately relayed to us by email and more interesting cases are also transmitted by SMS text message. Experience so far indicates that almost all cases of interest involve erroneous astrometry reports or artificial objects, e.g., the Hayabusa 2 spacecraft.