THE DIGEST2 - NEO CLASSIFICATION CODE Peter Vereš[1], M.J. Payne[1], M.J. Holman[1], S. Keys[1], Harvard-Smithsonian Center for Astrophysics, Minor Planet Center. 60 Garden Street, Cambridge, MA 02478, USA; pveres@cfa.harvard.edu

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Introduction:

Digest2 is a program for the classification of short-arc orbits that has been serving the NEO community for over 12 years. Its algorithm is similar to the statistical ranging technique and provides a pseudo-probability that the tested short-arc tracklet belongs to a given Solar System orbit type. For a short-arc, a set of possible orbits is generated in the so-called admissible region (Figure 1). Orbits are assessed with respect to the known orbit catalog and full population model [1] and a pseudo-probability digest2 score (0-100) for orbit categories is derived. Digest2 is mostly used for the classification of newly discovered NEO candidates in a need of rapid follow-up. The Minor Planet Center sets a threshold score ($D_{crit} = 65$) to dictate whether the object will appear on the NEO Confirmation Page[1], and hence whether it will be likely to gain attention from the follow-up community.

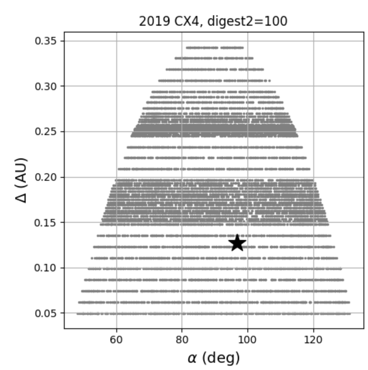

Figure 1: Grid of bound variant orbits generated by digest2 for a discovery tracklet of NEO $2019\,CX4$, showing the geocentric distance Δ and angle α between Δ and the velocity vector. Star shows the true position.

Simulations:

We tested digest2 on (i) tracklets selected from real observations of NEOs and non-NEOs, (ii) simulated tracklets based on real and synthetic orbits [1], and (iii) tracklets generated in a theoretical all-sky survey with current detection capabilities as well as the future LSST cadence [2]. The motivations for the simulated survey and model population was to avoid observational biases [3] and to compare observed objects in future observational programs. We focused on metrics such as accuracy, precision, false positive and false negative rates and effects of randomness, astrometric uncertainties and the identification of very near Earth flybys.

The main simulation was based on a synthetic population [1], from which we generated 20-minute tracklets, nightly for 10-years, spanning ± 100 degrees east and west from opposition and brighter than +22.5 Johnson's $V-band$ magnitude, simulating the current NEO survey capabilities.

One of the main outcomes of our simulations is a confirmation that NEO digest2 scores vary as a function of sky-plane location and rate of motion and at any given time, 28% of NEOs had $D < 65$. 94% of NEOs reach $D = 100$ at some point. Only 0.4% of NEOs never reach $D > 65$.

In absolute numbers, Jupiter Trojans dominate in D between 55 and 90. For $D > 90$, NEOs are most numerous, followed by Mars Crossers, Main Belt asteroids and Hungarias. Main Belt asteroids have the median D=0.

On average, the NEO digest2 score does not vary uniformly on the sky. Due to the geometry, rate of motion and confusion with the background populations, mainly with the Main Belt asteroids, relatively low NEO scores are 100 to 60 degrees west and east of opposition and 15 degrees within the ecliptic (Figure 2). Digest2 score is always large (D=100) at high ecliptic latitudes and for fast moving objects ($>$ 1 deg/day).

Special orbits:

In addition to regular NEOs there are particularly interesting objects belonging to NEOs that are that unusual, but also scientifically interesting.

'Oumuamua was the first discovered interstellar object, found by the NEO survey (Pan-STARRS). Its digest2 score was $D = 100$ at discovery which attracted follow-up observations and allowed its fast orbit determination. We computed the digest2 score for all reported 'Oumuamua tracklets. The digest2 score was equal to 100 for most of the times and always when $V < 22$. This result was in accordance with [4]. We showed that NEO digest2 score is a good indicator for discovery of interstellar objects.

[1] . . .

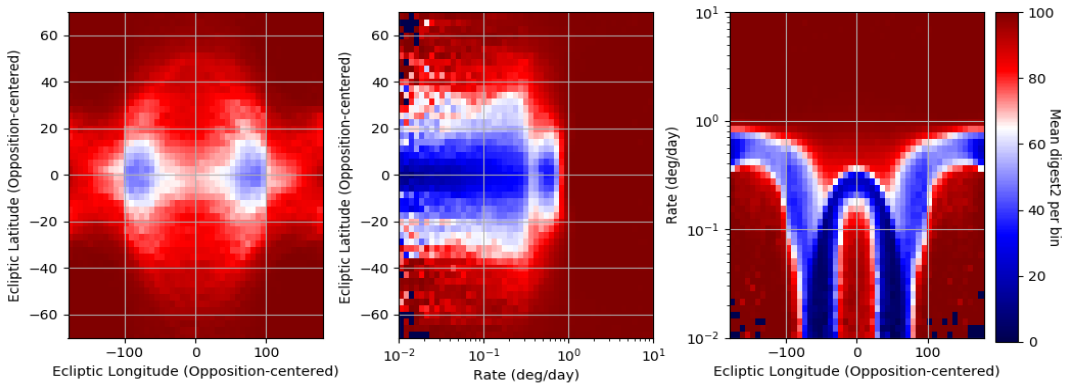

Figure 2: **Digest2 score for synthetic NEOs in a 10-year simulation in opposition-centered ecliptic coordinates per-bin mean digest2. digest2 is generally smaller at low solar elongation but also for slow moving NEOs.**

Some sub-population of NEOs are difficult to observe and face serious observational bias, such as Atens and Atiras. We computed digest2 score for Atens and Atiras from a synthetic population [1] in a hypothetical 10-year all-sky survey and showed that digest2 score is large, almost $D = 100$ in all cases for this class of NEOs.

Earth Trojans, quasi-satellites [5], co-orbitals and minimoons [6, 7] have peculiar NEO orbits and usually unique sky-plane motion. We generated tracklets for known objects in these categories[2], for 20-year time-frame and studied the behavior of digest2 score. The score is very similar to NEO scores and usually very large. The Earth's Trojan 2010 TK7 has digest2 always between 93 and 100, less than half of the time equal to 100.

Nearby NEOs are changing viewing geometry, apparent brightness and motion rapidly and due to Earth parallax, the motion is often not following the great circle even in a short 30, or 60-minute tracklet. We generated 20-minute, 4-detection tracklets for all known close approaches within $0.2\,au$ from Earth between years 2006 and 2018 and studied great-circle-departure (rms) and the digest2. Clearly, rms increases as a function of topocentric distance, same as rate of motion. We found out that there are no fast-moving, nearby NEOs or NEOs with non-linear motion, that have low digest2 score.

Code availability: Digest2 is a publicly available[3] C-program, that is distributed with the binned population model - both the known orbit catalog and full model, as well as default settings and astrometric uncertainties for several observatory codes. Digest2 has been in development for more than 12 years. It accepts 80-column astrometry format[4] for optical, radar, roving and satellite observations. Future improvements include implementation of ADES astrometry format[5], improved population model of the Solar System, performance tests for future space-based telescopes, such as NEOCAM and software tools like python wrappers.

Conclusion: We demonstrated that NEO digest2 varies as a function of time, rate of motion, magnitude and sky-plane location. We found out that NEOs tend to have on average lower digest2 score at low Solar elongations, near the ecliptic. 94% of of NEOs simulated in all-sky survey achieved the maximum digest2 score at least once and 99.6% of NEOs achieved the current Near-Earth Object Confirmation Page (NEOCP) digest2 threshold.

References: [1] T. Grav, et al. (2011) *pasp* 123:423 doi. [2] P. Vereš, et al. (2017) *aj* 154:12 doi. arXiv:1706.09398. [3] R. Jedicke, et al. (2002) *Observational Selection Effects in Asteroid Surveys* 71–87. [4] T. Engelhardt, et al. (2017) *aj* 153:133 doi. arXiv:1702.02237. [5] C. de la Fuente Marcos, et al. (2016) *mnras* 462:3441 doi.arXiv:1608.01518. [6] M. Granvik, et al. (2012) *icarus* 218:262 doi. arXiv:1112.3781. [7] B. Bolin, et al. (2014) *icarus* 241:280 doi.arXiv:1406.3534.

[2] (3753) Cruithne, (164207), (277810), (419624), (469219), 2002 AA29, 2006 RH120, 2010 TK7

[3] https://bitbucket.org/mpcdev/digest2/

[4] https://minorplanetcenter.net/iau/info/ObsFormat.html

[5] https://minorplanetcenter.net/iau/info/ADES.html