REAL-TIME SYNTHETIC TRACKING FOR NEAR-EARTH ASTEROIDS DETECTION Mălin Octavian Stănescu[1,5], Marcel M. Popescu[1,5], Ovidiu Văduvescu[2,3,4,5], Lucian Curelaru[1], Daniel Nicolae Berteșteanu[1,5], Marian Predatu[2], [1]Astronomical Institute of the Romanian Academy, Bucharest, 5 Cuțitul de Argint, 040557 Romania; TO mpopescu@aira.astro.ro & CC malin.stanescu@gmail.com; [2]University of Craiova, Craiova, Str. A. I. Cuza nr. 13, 200585 Romania; [3]Isaac Newton Group (ING), Santa Cruz de La Palma, Canary Islands, E-38700 Spain [4]Instituto de Astrofísica de Canarias (IAC), C/ Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain, [5]Astroclubul București, 21 Lascăr Catargiu, Bucharest, Romania

Keywords: *near-Earth objects, detection, synthetic tracking, parallel processing*

Introduction: The surveys targeting the detection of near-Earth objects (NEOs) are a key component for planetary defense. While the current surveys have discovered most NEOs larger than $1\,\text{km}$, and have made significant progress for detecting asteroids larger than $100\,\text{m}$, smaller objects tend to be discovered only during close flybys. This is due to their very faint apparent magnitude limit for most of the time. Recent examples of minor planets entering the atmosphere are the 1908 Tunguska event, where over $2000\,\text{km}^2$ of forest burnt due to an object whose size is estimated to be less than $100\,\text{m}$. Similarly the shockwave of the 2013 Chelyabinsk super-bolide has injured over 1200 people.

Conventional methods of detection based on (automated) blink technique require large aperture telescopes for observing the faint apparent magnitudes of these smaller NEOs. Since the cost of telescopes increases steeply with the aperture, the blink method (which is the most common one used to find asteroids) is increasingly prohibitive as the targets decrease in size. However, the detection technique known as Synthetic Tracking[1][2][3][4] (or Digital Tracking) allows the use of smaller telescopes (albeit with longer integration times) where the detections can be significantly under the noise floor of individual images. Thanks to modern computational resources, it is possible to combine the images to increase the signal to noise ratio across all possible trajectories of a faint potential moving object.

Here we present a moving object detection software called Synthetic Tracking on Umbrella (STU), which leverages the power of modern GPUs to perform this new detection method. The software is based on the Umbrella2 library [5], previously developed to perform the blink detection method, as well as auxiliary functionality necessary for a complete detection processing pipeline. Thanks to innovative search strategies, this software can perform near real time detection of fast-moving Near Earth Asteroids, even on large, multi-CCD instruments.

We show the functionality of this new software package using the observations performed with a various telescopes, including the $2.54\,\text{m}$ aperture Isaac Newton Telescope (INT). The validation tests included the processing of more then 100000 images obtained in various conditions (variable seeing, detectors with different noise level, pixel scales, field of view, objects with different apparent magnitudes, and moving rates). As example we present the detection of 2023 DZ_2. This near-Earth asteroid, formerly catalogued as Virtual Impactor, was discovered by our group during an observing run with the INT telescope between February 27, and March 1 2023 (MPEC 2023-F12[1]).

Methods: The full processing pipeline (Fig. 1) is split into the image processing pipeline (IPP), which handles image correction and field solving, such that further pipelines only need to be concerned about detecting objects, and the detection pipeline (STU), which performs the actual Synthetic Tracking operation.

The STU detection software is a pipeline combining image processing operations, an optimized brute-force scan and multiple automated pre-validation checks. The image processing operations handle operations of specific utility to synthetic tracking, such as adjusting the inputs to the correct format expected by the GPU algorithm and removing distracting elements such as fixed stars and sky gradients (which are not removed by flat field correction). The brute-force scan is performed on the GPU, simultaneously using shift-and-add as well as shift-and-median. Multiple tricks and optimizations are used to decrease the runtime, yielding very low scanning times, presented in the results section. Finally, the pre-validation checks combine the results from the brute-force scan into potential candidates and perform more expensive operations, involving cross-pixel correlations as well as measurements properties of the detected light sources that are used to filter out sources that are very unlikely to be real objects and are most probably outstanding image defects or noise.

[1] `https://minorplanetcenter.net/mpec/K23/K23F12.html`

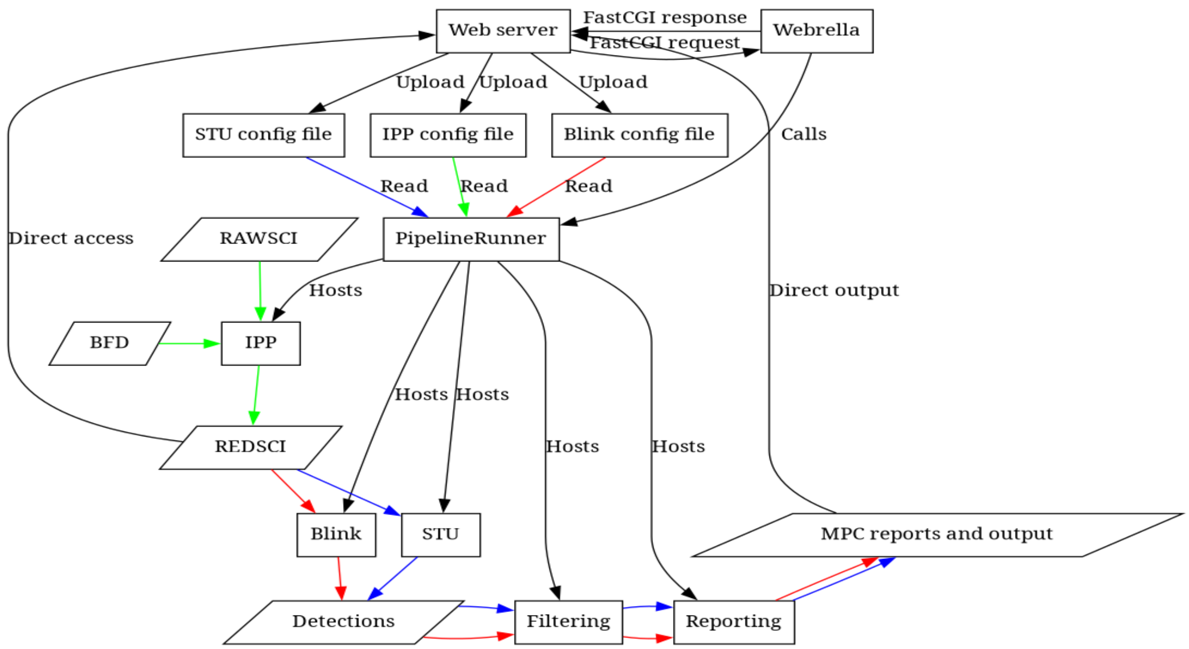

Figure 1: Schematic of our project including the IPP (Image pre-Processing Pipeline), and the STU (Synthetic Tracking on Umbrella) modules.

The output of the detection pipeline consists of MPC optical reports and associated data, such as stacked images of the detections (stamps), and CSVs containing many of the measured properties. Note however that the entire pipeline is modular, with detection methods, measurements and reporting formats being interchangeable.

Evaluation: To validate our algorithm we take advantage of observations performed with various instruments, including:

1. the Wide Field Camera (WFC) mounted on the $2.5\,$m Isaac Newton Telescope (INT) – about 3000 images;
2. the MuSCAT2 instrument [6] used by the $1.5\,$m Telescopio Carlos Sánchez (TCS) – about 120000 images;
3. the active pixel (CMOS) camera QHY294M mounted on T025 - BD4SB [7] – a $0.25\,$m, f/4, Lacerta telescope of Astronomical Institute from Bucharest – about 10000 images;

A python script was used to compare the MPC reports from STU with the expected objects in the field, which were obtained from SkyBoT [8] in an automated way. This was necessary for scanning the entire testing dataset, which contains a large collection of images.

Systematic tests of STU were done using the data obtained by the MuSCAT2/TCS instrument. The test sample included about 120000 exposures acquired in the framework of the program dedicated to 'Simultaneous observations in four optical bands of near-Earth asteroids using TCS/MuSCAT2 instrument' [9]. Two-thirds of the test sample were clear of pre-processing issues (no flat field issues, and no trailed images), had astrometry accurate to less than the pixel size ($0.434''\,$px^{-1}), and about 80% of the field was common for all exposures. Target objects of this dataset have a signal to noise ratio larger than 20 on the stacked image, obtained from individual exposures of $30\,$s over a total exposure time of $\approx 1\,$h. On this subset, where the SNR of the imaged NEAs on individual images is ≈ 2, STU has achieved 100% detection rate. The same detection rate (no objects missed) was also found for the high quality images obtained with QHY294M on T025 - BD4SB. Systematic tests are underway to characterize the detection rate with respect to SNR and with the number of exposures, with the total exposure time and image defects.

A second set of validation tests were performed using images obtained with the Wide Field Camera (WFC) mounted on the $2.5\,$m Isaac Newton Telescope. This is an old charge-coupled device camera which has more defects (dead and hot pixels) than modern sensors. Nevertheless, the INT has the advantage of the wide aperture which allows observations of objects fainter than 23 magnitude on individual exposures. The observing strategy was different for this telescope: we acquired continuous sets of 12 to 15 images with an exposure time between $30\,\mathrm{s}$ and $60\,\mathrm{s}$. The preliminary results show a detection rate large than 50% which is strongly dependent on the proper motion of the object (the STU algorithm often identifies objects with low apparent motion as background source to be masked out) and on the SNR, particularly in the presence of image gradients. Nevertheless, the NEAs with SNR larger than 10 (on the stacked exposure), and an apparent motion around $1\,''\,\mathrm{min}^{-1}$ or larger were always detected. In the next section we present two key detections of STU. Currently, we are integrating these images into the systematic testing suite.

Recent discoveries and recoveries (real-time validation run during 27th of February – 1st of March 2023): The Umbrella software was used for real-time processing of data from the INT WFC for the validation mini-survey performed between 27th of February and 1st of March 2023. The primary goal was to check whether the pipeline is ready for real-time data reduction in the context of a live survey. It was expected that the detections from STU would not be reported to MPC, as accuracy validation efforts were not yet completed, it was unknown whether STU provided enough positional accuracy by itself. Since this was a live survey, human validator focus was on creating validation data for STU using 3rd party tools (Tycho Tracker and Astrometrica), which could also be sent to MPC.

The virtual impactors 2023 DW and 2023 DZ$_2$
As a key test, STU detected 2023 DW (figure 2) and measured its position without any *a priori* information (the object was processed as a regular unknown object). The image reduction step (IPP) of this data set took $5\,\mathrm{min}$, with the STU pipeline taking an additional $26\,\mathrm{s}$ per CCD. The total processing time thus was $7\,\mathrm{min}$ per field on our main reduction system, which is $\approx 60\%$ of the data acquisition time. STU aims to work in real-time to reduce data at least as fast as the survey cadence, even for larger surveys; for INT WFC this was proven possible. We were not able to detect 2023 DW using other commercial software in the synthetic tracking search mode, as its proper motion required an impractically large amount of time for processing. Given the same software was able to detect the object in track and stack mode, we have all the reasons to believe this detection would have been possible for said software, should it be left scanning sufficiently long.

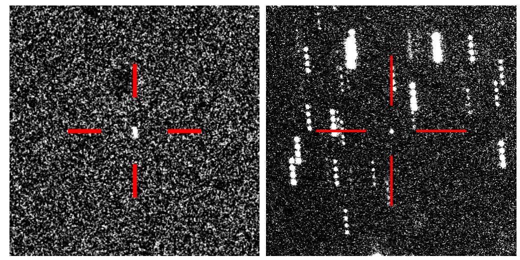

Figure 2: **Two key examples for our algorithm: 2023 DW (left) and 2023 DZ2 (right), also showcasing different detection stamp available for validation.**

Our top discovery during this observing run was the detection of 2023 DZ$_2$. Although detected earlier by STU, its first identification and validation was reported from the independent and parallel validation with other commercial software solutions. After the first detection during the first observing night we continued to follow it in order to obtain a longer orbital arc. The results were published in the Minor Planet Electronic circular MPEC 2023-F12 – `https://minorplanetcenter.net/mpec/K23/K23F12.html`.

Model for detection probability: STU uses as the main detection threshold during the brute-force scan the level of the median image (it can in fact use any percentile for the sorted list of pixel intensities). The detection probability can be calculated in this case using a combination of the normal distribution and the binomial distribution. This model does not cover the incidence of bad image areas (being them hot pixels or dead pixels).

The results of this model can be found in figure 3. As seen there, the detection probability for an object of the same SNR as the detection threshold is 50%, regardless of its intensity. Notably, the detection probability for an object with SNR ≤ 0 means in fact the false positive probability for a single-pixel hypothesis. Given the large search space of STU, even minute probabilities can become significant given enough motion vectors and image size. For this reason, the false positive probability for the brute-force search is computed separately.

While this rate applies only to the brute-force search and not to the whole STU, it is nonetheless important, as subsequent filtering and automated pre-validation checks are increasingly expensive. Therefore, the detection threshold must be adjusted to not overload the later stages of the pipeline; otherwise the runtime tanks. Currently, the number of candidates flowing into the next stage is considered within expectation when falling in the range $10^3 - 10^5$.

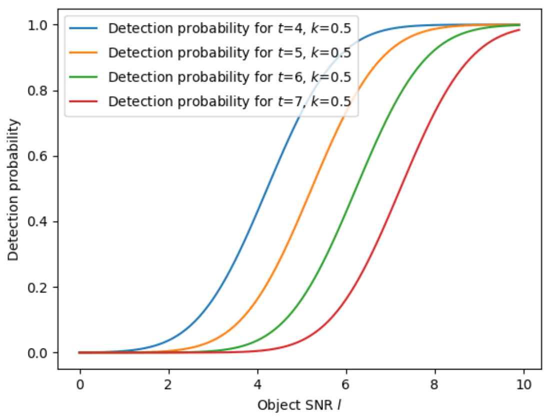

Figure 3: Theoretical detection probability for a stack of 30 images. Object SNR is l and detection threshold is t. Values for median image ($k = 0.5$).

Conclusion: Here we have previewed a real-time synthetic tracking system for detecting Near-Earth Asteroid. As part of our work, we have:

- shown that Synthetic Tracking is not as expensive as was once thought, and in fact it can now be done at survey speed. We have implemented STU to satisfy this real-time requirement.
- tested STU on a large number of images, from different telescopes. Results show good performance on clean input images. Effort is still underway to accurately understand the remaining limitations in detection rates.
- deployed an end-to-end image reduction and object detection pipeline.
- proved real-time reduction capabilities in field testing, with the February INT WFC run.
- validated the algorithm on one follow-up observation of a risk-listed asteroid and on a new discovery of a virtual impactor.

Going further, analysis of the cases where STU did not detect objects to identify the underlying reason continues for the currently large data set of images available to us. Efforts are also underway to improve the reporting and validation of detections from STU.

Acknowledgements: This work was developed in the framework of the EURONEAR collaboration[2], and it is financed by a grant of the Romanian National Authority for Scientific Research and Innovation CNCS - UEFISCDI, project number PN-III-P2-2.1-PED-2021-3625. We would like to thank all students and collaborators who helped us during this run, including Freya Barwell, Kiran Jhass, Carlos and Raul de la Fuente-Marcos, and prof. Costin Boldea who was the first to validate 2023 DZ2 (using Tycho Tracker).

References: [1] B. Gladman, et al. (1997) *Astronomy and Astrophysics* 317:L35 doi. arXiv:astro-ph/9610150. [2] T. Yanagisawa, et al. (2005) *Publications of the Astronomical Society of Japan* 57(2):399 ISSN 0004-6264 doi.arXiv:https://academic.oup.com/pasj/article-pdf/57/2/399/17265372/pasj57-0399.pdf. [3] C. Zhai, et al. (2018) Technical note: Asteroid detection demonstration from skysat-3 b612 data using synthetic tracking. arXiv:1805.01102. [4] M. Shao, et al. (2014) *The Astrophysical Journal* 782(1):1 ISSN 1538-4357 doi. [5] M. Stănescu, et al. (2021) *Astronomy and Computing* 35:100453 doi.arXiv:2008.04724. [6] N. Narita, et al. (2019) *Journal of Astronomical Telescopes, Instruments, and Systems* 5:015001 doi. arXiv:1807.01908. [7] D. Nicolae Berteșteanu, et al. (2022) in *European Planetary Science Congress* EPSC2022–1222 doi. [8] J. Berthier, et al. (2006) in *Astronomical Data Analysis Software and Systems XV* (Edited by C. Gabriel, et al.) vol. 351 of *Astronomical Society of the Pacific Conference Series* 367–+. [9] M. Popescu, et al. (2021) in *European Planetary Science Congress* EPSC2021–820 doi.

[2]http://www.euronear.org