Finding Asteroids with the Zwicky Transient Facility

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Abstract

Near-Earth Asteroids (NEAs) are of primary concern as they pose threats to our civilization and provide considerable opportunities for resource utilization in future space activities (Waszczak et al, 2017). Although many NEAs have successfully been discovered using previously implemented detection algorithms, efforts to accurately detect fainter and thicker streaks have been hindered due to a lack of sensitivity and precision in the current methods used. As a tradeoff, increasing the number of real asteroid streaks (i.e. the "true positives") inevitably leads to the increase of falsely detected streaks (the "false positives"), which we aim to reduce. To overcome these limitations, an image-segmentation approach has been devised using an online resource named ASTRiDE (Automated Streak Detection for Astronomical Images) to trace out the boundary of various shapes in astronomical images and output their morphological parameters, which are in turn used to classify the objects and filter out false positives using carefully constructed filtering schemes. We've devised an area to perimeter (A/P) ratio as an initial filtering scheme. We specifically explore this ratio and try to find a thresholding value that would allow us to accomplish our goal of yielding additional fainter and thicker streaks and reducing false positives at the output.

1. Introduction

One of our greatest and ever-growing interest is to understand the formation of our Solar System. We have been successful in observing large astronomical objects, but not as much with smaller-sized ones such as near-Earth objects (NEOs), main-belt asteroids, and various other smaller groups of asteroids and comets. The study of small objects greatly contributes to the understanding of various fundamental questions in planetary science such as the composition of the proto-planetary disk, the evolutionary history of the Solar System, as well as the transportation and distribution of water and organic materials in the Solar System. NEOs are of particular interest because they pose threats to our civilization and provide considerable opportunities for resource utilization in future space activities. Our current knowledge of the distribution of km sized NEOs is rather complete (Jedicke et al. 2015) yet drops sharply towards the smaller sizes. Detecting these small asteroids is rather challenging since they are either very faint when they are far from Earth or have large motion rates when close and bright enough to be detected. NEOs that approach Earth at a closer distance typically move at a very fast rate and are designated the term "Fast-Moving Objects" (FMOs) as well as "streaked" objects, seeing that they noticeably move during long exposure times. They also present a challenge for traditional NEO detection algorithms, which aren't quite fashioned to detect objects moving at such speeds. However, the survey data from the Palomar Transient Factory (PTF) (Waszczak, Kulkarni et al, 2017) successfully demonstrated a prototype pipeline dedicated to FMO detection with the 1.2m Oschin Schmidt telescope equipped with the 7.3 deg CFH12K camera. PTF was later succeeded by the Zwicky Transient Facility (ZTF, Shri Kulkarni, Principal Investigator) (Bellm, E.C. et al, 2019) which improved upon the apparatus adopted by its predecessor. Data acquired by ZTF's (and previously PTF's) telescope are transmitted to the Infrared Processing and Analysis Center (IPAC) at Caltech where they are processed in real-time (Masci et al. 2019). The detection process consists of four steps: the "initial detection", the "streak point-spread-function fitting code", the "machine-learned classifier," and the "human scanning and streak-linking" (Ye, Quanzhi et al, 2019). The first step consists of searching for linear image features that resembles the appearance of trailed sources in "difference" images, while the second, third, and fourth, act as filters against unreliable detections; the first two are computational-based filters while the last is human observation-based. Difference images are images generated by subtracting "reference" images from the raw images, where reference images are simply the "static" representations of the sky, constructed from co-adding historical science images acquired earlier in the survey (Masci et al, 2019.

While machine learning has been one way of removing false detections, it placed a huge strain on computing resources and limited the turnaround time of reporting discoveries. We instead sought alternative measures by implementing streak-detecting algorithms from scratch, to ensure a higher true/false detection rate made by detecting more streaks (i.e. fainter and shorter ones) and by reducing the false positive rates by implementing several filtering schemes.

2. Methods

We extended an algorithm implemented in an existing software tool called ASTRiDE (Automated Streak Detection for Astronomical Images) to improve the reliability of detecting fast moving asteroids in the image data stream. ASTRiDE essentially aims to detect streaks in astronomical images by tracing the border of each object in the image (i.e. boundary or contour tracing) and by outputting a list of morphological parameters for each of the detected objects. The way the software tool works is by first removing the background (noise) from the image by calculating the background level and its standard deviation, and then proceeding to deriving the contour map, that is, the borders of all objects in the image. Each detected object by ASTRiDE has associated with it some output morphological parameters such as the area, perimeter, coordinates, shape factor, and radius deviation. Since streaking asteroids are our object of concern, we would like to only consider objects that are long and relatively thin when compared to other celestial objects such as stars and star-like sources. ASTRiDE takes care of that by setting thresholds on several morphological parameters, with the most crucial ones being the shape factor and the radius deviation which both represent a measure of circularity. Since our aim is to detect shorter and fainter streaks, the thresholding values of the previous parameters had to be more loosely set, which inevitably led to a bigger influx of false detections. From the analysis of a wide set of astronomical images containing real asteroid streaks, an area-to-perimeter ratio was devised as a preliminary initial filtering scheme to try and reduce the amount of false detections obtained at the output without sacrificing too many true detections. We further explore this ratio by collecting vast amount of data and by trying to find a thresholding value that will help us accomplish our goals.

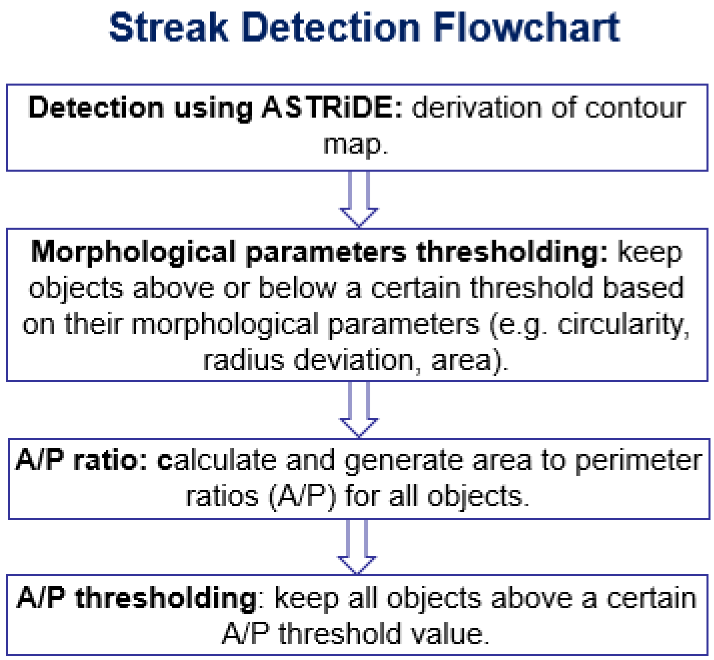

Figure 1: Flowchart displaying the previously laid out steps for streak detection.

3. Results

After analyzing 36 different astronomical images containing real streaks, we collected a total of 15 true detections and 3303 false ones. Example cutouts are shown below:

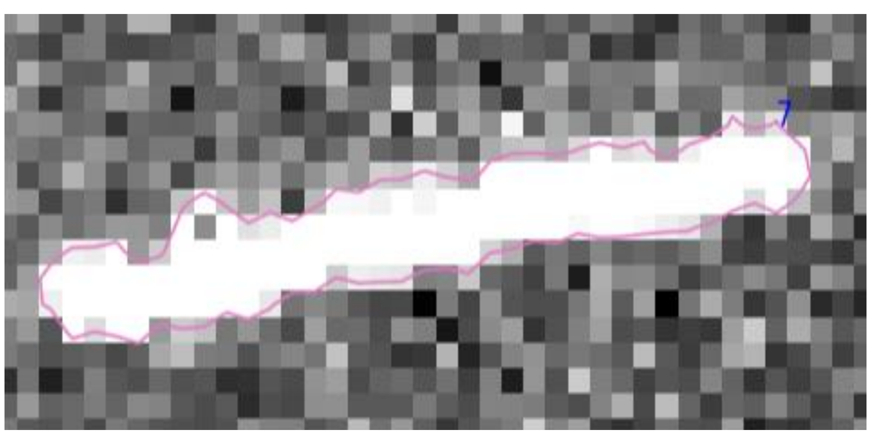

Figure 2: True detection (real streak); A/P = 1.52.

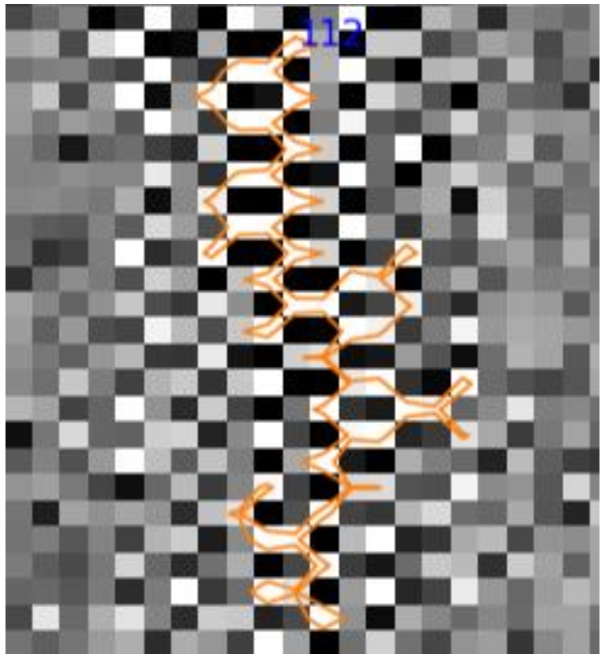

Figure 3: False detection (due to artifacts in the numerical filter used to match the resolution of the new and reference images before subtraction); A/P = 0.30.

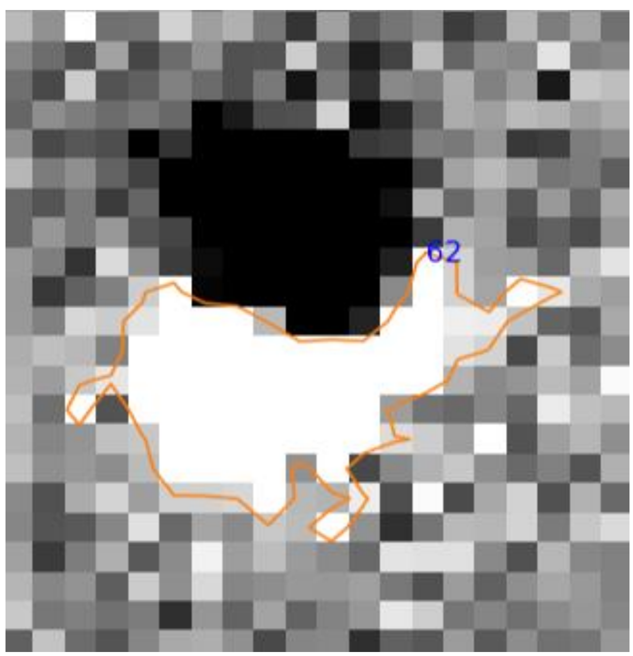

Figure 4: False detection; A/P = 1.12.

We then plotted the objects' surface brightness magnitudes (the higher the value, the lower the brightness) versus their A/P ratio (as shown in figure 5 below), augmenting our analysis to include the surface brightness magnitude as an additional potential parameter to choose to implement as a filter.

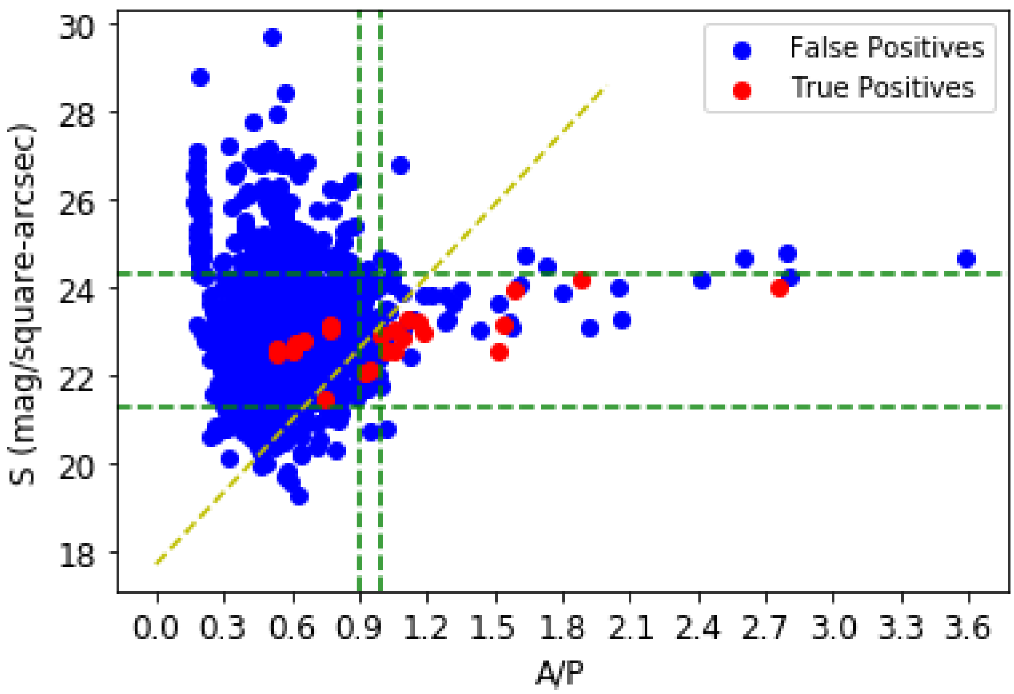

Figure 5: Surface brightness magnitude vs A/P, with red points representing true positives and blue points representing false ones.

We can see from the plot that if we were to choose A/P = 0.9 as a thresholding value, the ratio of true positives to false positives for A/P < 0.9 would be equal to 0.25% and the ratio of true positives to false positives for A/P > 0.9 would be equal to 16%. If we instead choose A/P = 1.0, the ratio of true positives to false positives for A/P < 1.0 is equal to 0.3% and the ratio of true positives to false positives for A/P > 1.0 is equal to 29.5%. Therefore, choosing a value between 0.9 and 1.0 has shown to be most effective in reducing the false positive rate.

To pinpoint an exact value within that range then requires more real streak data to be acquired and analyzed. We can also see that an additional surface brightness magnitude filter (thresholding a minimum and a maximum) could be effective in reducing the number of false positives, as shown by the green horizontal dashed lines in Figure 5. A combination of an A/P and a surface brightness magnitude filter could also be seen to be effective in leaving out many false positives, as seen from the zone where the true/false positives ratio is rather high below the yellow dashed line.

4. Analytical Approximation

If we then allow ourselves to approximate the streak to have a rectangular shape with length L and width W, we get an area A = WL and a perimeter P = 2W + 2L. Assuming W ~ 2, the A/P ratio is reduced to be equal to $\frac{A}{P} = \frac{2L}{2L+4}$. For the shortest streaks, we assume L ~ 3, which leads to A/P ~ 0.6 which is comparable to the lowest A/P values for true positives. For streaks L > 8, we get A/P > 0.8, which in turn corresponds to the areas in Figure 5 with the highest percentages of true positives.

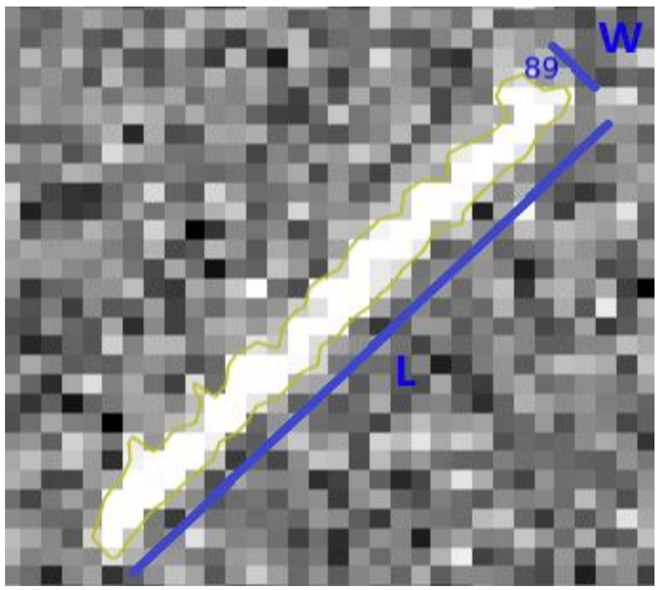

Figure 6: Real streak being approximated as a rectangle with width W and length L.

We hope that these results show that an image-segmentation approach with additional implemented filters could hold a place of great potential in successfully detecting streaked asteroids in astronomical images.

References

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