Tycho Tracker: A New Tool to Facilitate the Discovery and Recovery of Asteroids Using Synthetic Tracking and Modern GPU Hardware

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Abstract

Approximately 2100 Near Earth Objects (NEOs) are discovered each year. Nine out of ten are discovered at magnitude 19 and fainter. The conventional wisdom for those interested in discovering such objects has been that aperture is king. However, a relatively new concept -- synthetic tracking -- enables the discovery and recovery of such objects even with amateur-class telescopes. At the time of its introduction in 2013, it was largely dismissed as impractical due to the required computing power. Fast-forward seven years later to 2020, and graphics processing unit (GPU) hardware is now 10x faster at half the cost. Furthermore, the amateur astronomer now has access to full frame CMOS cameras that permit short exposures with low read-out noise. Finally, the new Rowe-Ackermann Schmidt Astrograph (RASA) telescopes offer an optimal pairing with the smaller pixels commonly encountered in modern CMOS cameras. Combining all three of these recent advancements leads to an exciting new frontier in the world of minor planet research and discovery.

1. Introduction

On January 22, 2020 an amateur astronomer discovered 2020 BW8, a Near Earth Object (NEO) approximately 21 meters in size within ten lunar distances of the Earth (MPEC 2020-B194). This was a full three days before it was reported by the professional surveys. At the time of discovery, it was observed at magnitude 19.8 and moving at 4.8 arcseconds per minute ("/min). The setup was that of a C14 telescope in Hyperstar configuration, and synthetic tracking was performed on 60 exposures taken of the same field, with each exposure being 60 seconds in duration. Of additional note is that this astronomer had just received a Minor Planet Center (MPC) observatory code one month prior to the discovery.

The concept of synthetic tracking as it relates to the discovery of minor planets can be traced as far back as 2013 when Dr. Shao of the Jet Propulsion Laboratory (JPL) published a paper detailing how one could conduct a blind search using the "shift-and-add" technique that is more commonly used for asteroid recovery (Shao, 2013).

Shift-and-add refers to the concept of taking a sequence of images and "shifting" them a certain way and then stacking (or "adding") them together. It is most commonly used to recover objects having known motion. But with synthetic tracking, a sequence of exposures can be shifted and stacked in thousands of different ways to detect objects having a wide range of motion. As might be expected, this process is rather computationally intensive, and noted as such in the 2013 paper. But the GPU used at the time was a Tesla K20c, which cost $3200 and achieves a score of only 12k on the CUDA benchmark. In contrast, today one can acquire an RTX 2080 Ti GPU for around $1200 that achieves a score of 162k on the CUDA benchmark – approximately 13.5x faster.

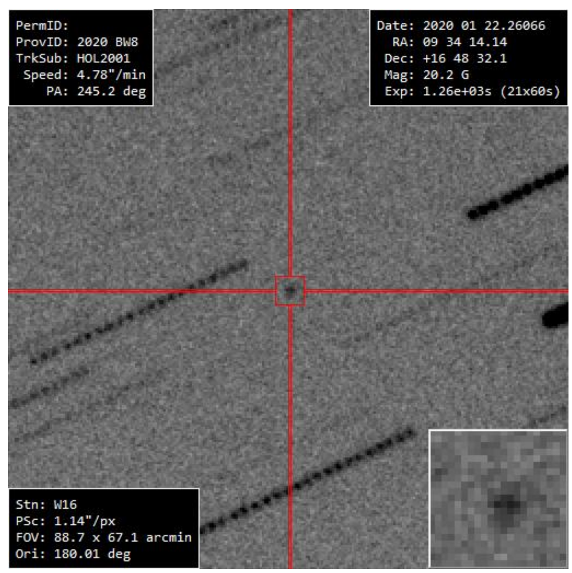

Figure 1. 2020 BW8, Discovered with Synthetic Tracking

Another paper published in 2015 by Dr. Heinze demonstrated the efficacy of synthetic tracking (referred to as "Digital Tracking" in the paper) in discovering main belt asteroids (Heinze, 2015). In this example, 215 asteroids were found over a two-night period using the 0.9m WIYN telescope. However, the software they used worked with CPU (Central

Processing Unit) rather than GPU algorithms, and consequently took 50 days to process the data at a rate of 8.1×10^{11} vector-pixels per hour. For comparison, a single RTX 2080 Ti achieves a processing rate of 1×10^{14} vector-pixels per hour, or 120 times faster.

In 2018, a single night of observing time was rented on a 127mm refractor. Even with this small telescope, it was possible to detect over 281 asteroids in a single 3x3 degree field of view, using synthetic tracking on a set of 50 three-minute exposures (Parrott, 2019b). The SNR improvement enabled the detection of very faint asteroids, including one that was detected at magnitude 20.8 – which is quite good for only 127mm of aperture. For comparison, using the conventional technique (which detects moving objects from four exposures), only 53 asteroids were detected.

2. Concept

Those who have used the “shift-and-add” (or track-and-stack) technique to recover faint asteroids should be familiar with the improvement in signal-to-noise ratio (SNR) achieved with the process. When the motion of the asteroid is known in advance, the images are simply aligned accordingly and then subsequently stacked. The resulting stack shows a nicely recognizable object compared to what would otherwise appear to be noise on a single exposure. The motivation behind synthetic tracking is to extend this concept one step further so that one can improve the SNR of objects having unknown motion. On the surface, one simply generates thousands of “trial stacks”, with each stack exploring a different motion vector. One then iterates over these trial stacks and extracts candidate detections. Finally, these candidate detections are then sorted by a quality metric.

3. Comparison with Conventional Technique

The clearest advantage of synthetic tracking is that it offers a massive improvement in SNR. Whereas the conventional technique is limited to the SNR of a single exposure, synthetic tracking can dramatically improve the SNR of an object by selecting the optimal trial stack generated for that object. And the selection of optimal trial stack is done automatically, without the need for user intervention.

Another advantage for synthetic tracking is that it is much less impacted by the number of stars in the image. The conventional technique operates by extracting all objects from each of its (typically four) exposures, and has to then determine if there is consistent motion from one frame to the next for each extracted object.

The result is that even the professional surveys avoid crowded star fields such as those near the galactic plane. But synthetic tracking does not have this shortcoming – it processes the entire field on a per-pixel basis independent of the number of stars in the image.

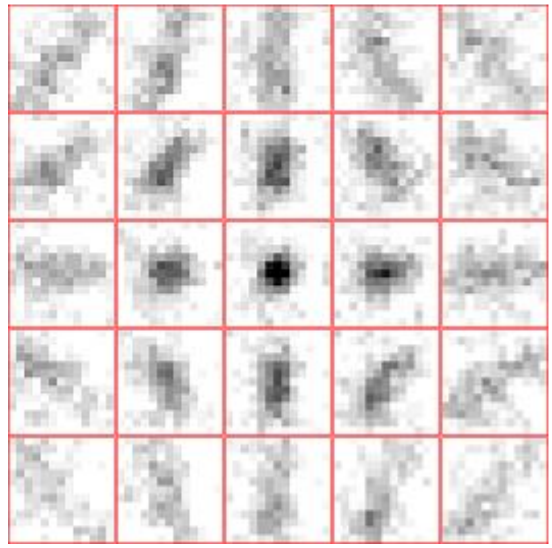

Figure 2. Trial Stacks of the Same Object.

Processing time is only one factor for crowded fields. The actual ability to detect the moving objects is another. In a crowded field, the probability that a moving object will pass in front of a star is much higher than otherwise. This reduces the likelihood that it will be detected by the conventional technique when it is indistinguishable from a star on one (or more) of the four frames.

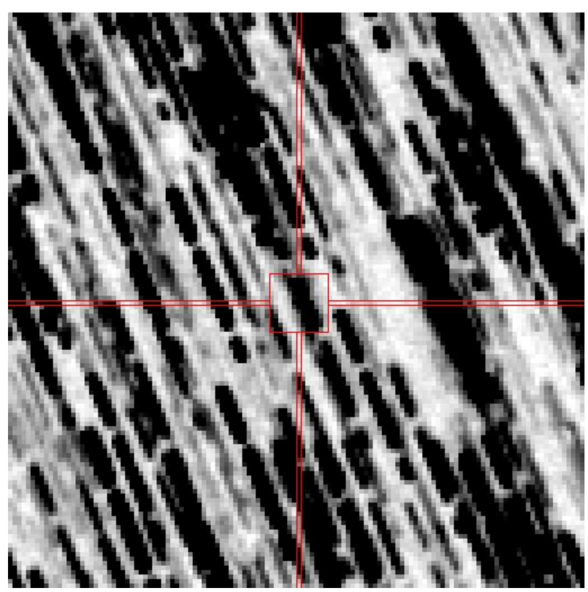

Figure 3. Average Combine in Crowded Field.

In comparison, with synthetic tracking, the trial stacks that it generates are quite effective at filtering stationary objects, thus allowing it to perform much better at identifying moving objects even in crowded fields.

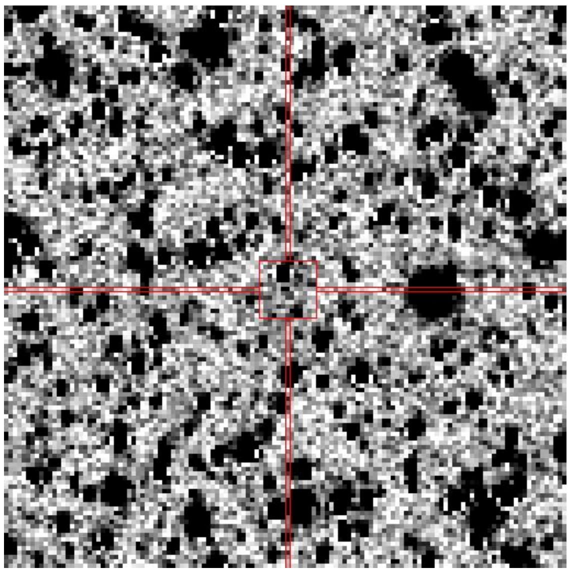

Figure 4. Single Exposure, Same Field.

As one example, consider the typical “average” combine that one might ordinarily perform with the ‘track and stack’ approach. An example of this is shown in Figure 3. With this stack, it is virtually impossible to detect the moving object due to the star interference. Also compare with that of a single exposure, shown in Figure 4. Again, the object is indistinguishable from the stars in the image.

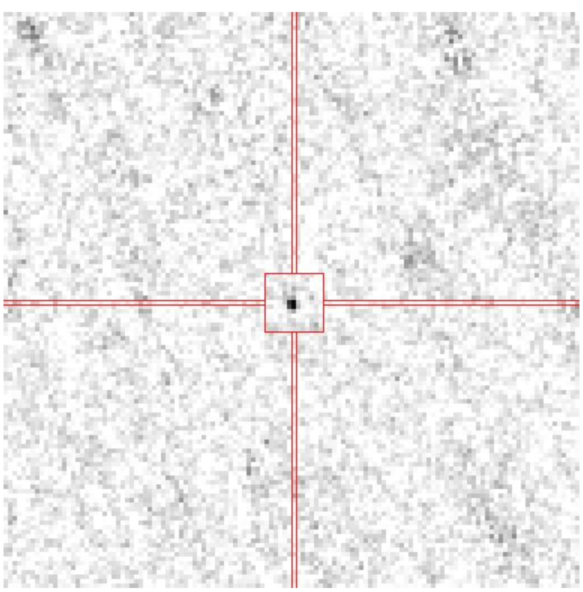

Figure 5. Synthetic Tracking, Same Field.

Finally, consider the stack shown in Figure 5. This is a trial stack generated by the synthetic tracking algorithm, and it is able to clearly show a moving object while suppressing the interference from stationary objects.

For an astrometry program, the ability to detect objects is only one part of the equation. The other aspect, and just as important, is the ability to accurately measure the objects.

4. Evaluation of Astrometry Measurements

Astrometry is concerned not just with the position of an object but also its associated time information. Therefore, in order to accurately evaluate the quality of the measurements generated by the Tycho software, one must have a dataset that takes into account both position and timestamp data. One such dataset was generated by examining a set of 25 NEOs imaged by four different observers. Each of these NEOs were originally measured using another astrometry program (Astrometrica). Then, the data were reprocessed in Tycho and new measurements were generated. This provides the basis to evaluate the quality of the measurements on objects having a wide range of position and timing information. Refer to Figure 6.

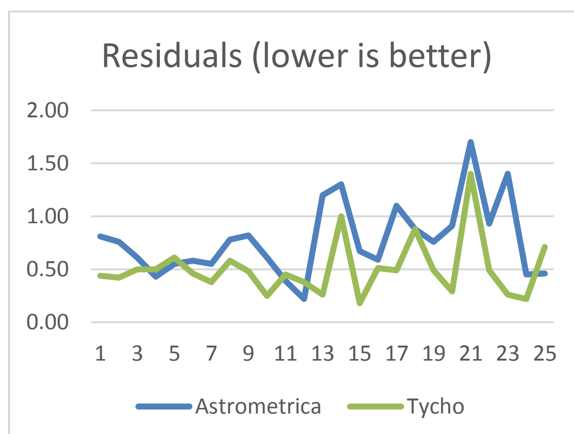

Figure 6. Measurements of 25 NEOs.

In order to evaluate the quality of a measurement, a residual is computed. Residuals indicate how far the measurement deviates from the expected value. In order to more accurately compute the expected value, the measurement, along with those produced by other observers of the same NEO, are combined into a single file. This file is then loaded into the FindOrb software (developed by Bill Gray) which is then able to compute the residuals for each measurement. The chart shown in Figure 6 indicates the residuals associated with the measurements generated by both

Astrometrica and the Tycho software. As three measurements were generated for each of the 25 NEOs, the highest residual is selected among the three. The unit is that of an arcsecond; thus, a residual indicates the deviation from the expected value in arcseconds, and therefore a lower residual is preferred. As can be seen from Figure 6, the Tycho software is able to produce very accurate astrometry measurements, especially in relation to the Astrometrica software which is also considered a sort of "gold standard" among those in the field.

5. Evaluation of Photometry Measurements

While the astrometry portion of an asteroid measurement is critical information, it is also desirable to achieve good photometry information when possible.

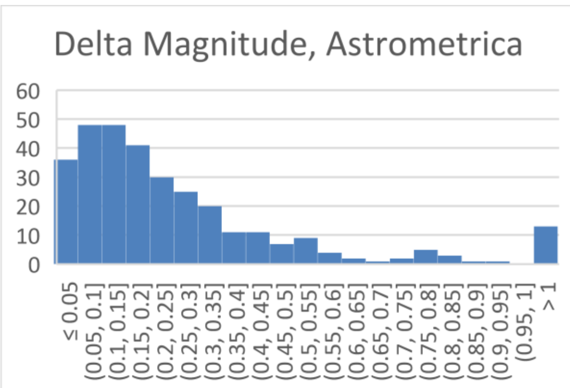

Figure 7. Delta Magnitude, *Astrometrica*.

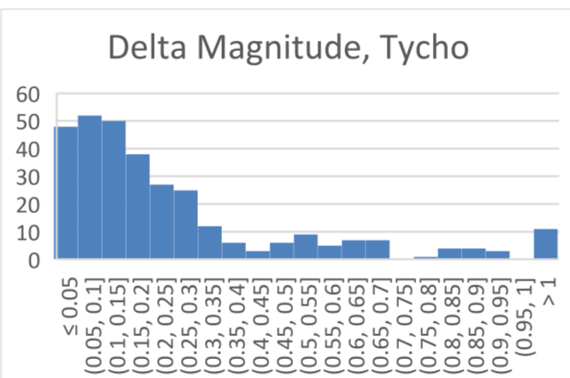

Figure 8. Delta Magnitude, *Tycho*.

In this test, an evaluation of the photometry measurements is achieved by taking an image and sampling hundreds of catalog stars. Thus, one is aware of the true magnitude, and the corresponding measured magnitude. From this one computes the delta magnitude, and similar to the residual described earlier, a lower value is preferred.

As before, the same image data is presented to both programs. Figure 7 presents a histogram of the delta magnitudes achieved with the Astrometrica software, and Figure 8 presents a histogram of the delta magnitudes achieved with the Tycho software. Both programs produce comparable histograms, indicating that the Tycho software is able to produce photometry information that is on par with the Astrometrica software.

6. Dwell Time and Limiting Magnitude

A 2018 paper by M. Shao et al indicates that a 28cm telescope can achieve a limiting magnitude of approximately 20.5 using a sequence of 100 exposures, each five seconds in duration (Shao, 2018). A 36cm telescope would yield a 0.5 magnitude improvement, and in conjunction with 790 seconds total exposure versus 500 seconds, it would therefore achieve an overall limiting magnitude of 21.5.

7. Economic Comparison

Synthetic tracking outperforms the conventional technique not just in terms of detection but also in economic terms. In order to detect fainter objects with the conventional technique, one must increase the aperture of the telescope. As is known, the cost of aperture increases exponentially with the diameter of the mirror.

But with synthetic tracking, one can (to a point) increase the dwell time on the field to detect the fainter objects. Again, this is not the same as simply increasing exposure time (as otherwise the asteroids would streak), but instead amounts to taking more exposures to increase overall dwell time. Discussion of the limits of dwell time can be found in the paper by Heinze, where it is shown that one can improve SNR by a factor of ten with synthetic tracking regardless of orbit class (NEO, MBA, or TNO).

Having increased the dwell time per field, the immediate downside is that sky coverage is reduced. However, it is more economical to have an array of smaller telescopes than it is to have one giant monolithic telescope. In order to fully appreciate this, some numbers are provided.

As an example, the Catalina Sky Survey operates three telescopes. Telescopes G96 and 703 are used for survey purposes, and I52 is used for follow-up. Since G96 outperforms 703 in discoveries, it will be used as the comparison telescope.

It takes G96 approximately 120 seconds to capture four 30-second exposures, each centered on the same field. Each field is 5.0 square degrees of sky coverage. The limiting magnitude is approximately 21.5. The efficiency of this system can be said to be 120 seconds/5.0 square degrees or 24.0 seconds per square degree of sky coverage.

For comparison, a RASA 14 telescope paired with an IMX455 sensor can cover 4.5 square degrees and reach the same limiting magnitude (21.5) in 790 seconds (refer to section "Dwell Time and Limiting Magnitude"). Thus, it has an efficiency of 790 seconds/4.5 square degrees or 176 seconds per square degree.

It can be seen from these numbers that the synthetic tracking system can achieve comparable efficiency by having an array of 8 small telescopes (from 176/24). The cost for each telescope sub-system is derived from that of a mount ($10k), the RASA telescope ($14k), and camera ($6k). This brings the initial cost for the array of telescopes to $240k. Computer resources, including the GPU hardware, are required to process the data, so one can budget $10k of hardware per subsystem, bringing the total to $320k. A roll-off roof can also be used to house the 8 telescopes, thereby avoiding the large expense of an observatory for each subsystem and distributing the cost of the structure across the 8 instruments. This could be budgeted for $500k, bringing the total to approximately $820k.

The above outlines the cost for a synthetic tracking system that would achieve the same sky coverage and limiting magnitude as that of G96, one of the most efficient survey systems based on data from 2019. Given that G96 is a 1.5m instrument paired with a custom 111 mega-pixel camera, its cost likely exceeds that of the above by a factor of ten.

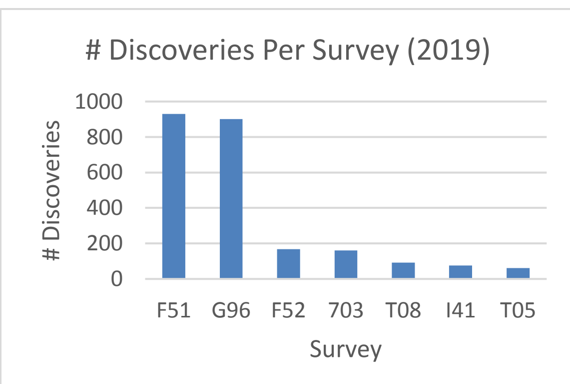

Figure 9. Comparison of Survey Performance.

An additional point of comparison is F51, which held the number one spot in 2019 with just a few more discoveries than G96. F51 is also more commonly known as PanSTARRS, or alternatively PS1, since there is also F52 which provides a second survey instrument. Regarding F51, it has a slightly larger mirror than G96, 1.8m versus 1.5, and it reaches a limiting magnitude of 22.7 versus 21.5. It also has a slightly larger field of view at 7 square degrees compared to 5 square degrees. Sources indicate a cost of $25 million per instrument for the PanSTARRS survey (Beatty, 2010). Accordingly, this would make a synthetic tracking survey approximately 25x more cost-effective, since at $820k it would deliver results that are on par with G96 and by extension F51. This also means that a synthetic tracking survey could be scaled up to deliver an order of magnitude more discoveries at comparable cost.

In addition to the cost-effectiveness described above, an array comprised of commercial off the shelf (COTS) telescopes offers additional advantages. For one, it can be scaled up easily, and the roll-off structure could be designed to accommodate more than just 8 instruments. Alternatively, one could install multiple 8-instrument surveys across different geographic locations with different weather patterns to offer better coverage. Finally, one could also optimize different segments of the array for different classes of targets depending on object speed, rather than using a single exposure time with a "one-size-fits-all" approach. For example, PanSTARRS maxes out at 10 degrees per day, equivalent to 25"/min (Do, 2018).

As a side note, Figure 9 also shows the importance of limiting magnitude. Even though the 703 survey telescope at Catalina has a significantly larger field of view than G96 (20 square degrees versus 5), it also has a much lower limiting magnitude at 19.5 versus 21.5. Consequently, it ranks #4 at only 161 discoveries compared with 901 discoveries for G96. Thus, the ability to reach magnitude 21.5 using COTS hardware is a key part of what makes synthetic tracking an optimal survey technique.

8. Discovery of Comets

A survey comprised of an array of smaller telescopes would also be more adept at discovering comets. This is because comets are generally discovered near the Sun. Consider the following excerpt (Walthert, 2015):

"That is because, for all their power, the big professional telescopes do have limitations that amateurs do not. For example, the big scopes cannot examine objects that are too close to the Sun, which could damage their sensitive (and expensive) optics. Amateurs, on the other hand, can do whatever they want with their telescopes without worrying about damage to $100 million instruments—the expected cost for the four Pan-STARRS scopes."

Combined with synthetic tracking, the smaller instruments would be able to simultaneously achieve comparable sensitivity to that of the larger instrument, while also being more immune to saturation that could damage their optics, thus permitting discovery of comets that are fairly close to the Sun.

A further advantage is that because synthetic tracking uses a series of dozens of exposures per field, as opposed to just three or four that are used by the conventional process, a single bad exposure does not render the field unusable. Contrast this with the conventional technique, where each of the four exposures must be of good quality for the detection algorithm to return valid results. This is becoming of increasing importance with the advent of satellite constellations.

9. Hardware Implementation

One can implement synthetic tracking in a number of ways. From a hardware standpoint, there are three main different approaches. The first of which is to design the algorithms purely for central processing unit (CPU) support. This offers the slowest approach as mentioned earlier. Second, one can use graphics processing unit (GPU) hardware which offers, at minimum, a 20x improvement in speed. Finally, one could also implement it with a field programmable gate array (FPGA) system, which is also faster than CPU, but not typically faster than GPU at the same price level.

The latter approach has been tested by a team in Japan by Yanagisawa, using a Nallatech H101-PCXM FPGA board. According to the paper (Yanagisawa, 2019), it was able to process 2.2e12 vector-pixels in 14 minutes, or approximately 9e12 vector-pixels per hour. Modern GPU boards are able to process at a rate of approximately 1e14, or about ten times faster.

A modern FPGA would likely achieve better performance numbers (the H101 uses an older Virtex-4 FPGA), but also at much greater cost. It is not uncommon for the higher-end FPGA boards to cost in excess of $8000, whereas a top-end GPU such as the RTX 2080 Ti costs around $1200.

Finally, GPUs are also more flexible than FPGAs. Adopting a different algorithm is as simple as loading a different code file. But with an FPGA, the logic gates have to be designed and configured to suit a particular algorithm, which is a project in itself. However, this specialized design does give FPGAs one advantage, which is that they are typically more power efficient than GPUs.

In brief, a GPU offers the highest performance at lowest cost, while also providing the greatest flexibility. Consequently, it is preferable to use GPUs for synthetic tracking, as processing time must be minimized to enable quick follow-up of NEO detections.

10. Stacking Technique

Another aspect of synthetic tracking that bears mentioning is the stacking algorithm itself. While it has been discussed at a high-level throughout this paper, the actual stacking process is a detail that can greatly impact the results.

In the Shao paper, they use “add and mean”, which delivers a stack comprised of images that have been added together, producing an average pixel value.

In comparison, both Heinze and Yanagisawa use median combine. This delivers a much better result because it can eliminate false positives much more effectively. This is also the approach that Tycho uses, in a slightly modified form so as to further improve detection of moving objects compared to that of stationary objects (refer to Figure 5).

11. Using Synthetic Tracking for Object Recovery

Another advantage with synthetic tracking is that it offers an improvement in the recovery of objects where the ephemeris information has high uncertainty. Whereas the standard “track and stack” approach explores only one motion vector, synthetic tracking automatically evaluates hundreds of motion vectors so as to identify the optimal vector associated with the object. This is particularly useful when there is high uncertainty in the motion of the object. This can occur when the object is discovered on one night and then the subsequent night has poor weather conditions, causing a delay in acquiring an improved set of orbital elements, leading to increasing uncertainty. Thus, the ability to automatically generate and evaluate candidate detections from a wide number of motion vectors can prove immensely useful in the recovery of otherwise “lost” objects.

Even when the motion of the object has low uncertainty, synthetic tracking still has yet another advantage in that it will automatically extract all objects having that particular motion and rank them by quality. Consequently, it is not necessary for the user to manually scan the image.

11.1 Recovery Example #1: 2019 MX1

2019 MX1 is a Mars Crosser asteroid found in June of 2019 with a 127mm refractor using synthetic tracking. While it was later linked to a previous discovery in 2008, it was not known at the time that this asteroid had been observed previously -- the Minor Planet Center “MPChecker” tool indicated no known previous detections. It was therefore desirable to acquire follow-up observations of the object to further refine its orbit.

A follow-up took place on June 27, 2019. Using observations from June 4, the resulting ephemeris indicated an expected motion of 0.93"/min at a position angle of 340 degrees. It also placed the object 21 arcminutes away from its actual position, such that any effort to follow-up the object would involve scanning a fairly wide area. This may be acceptable when the object is reasonably bright, but when it is a faint object, doing such manual scanning is a challenging endeavor. Figure 10 shows the recovery of the object, made possible with synthetic tracking. It can also be seen that the object passed in front of a star in this field. Despite this, it was still possible to generate accurate observations due to the specialized median layer generated by the tracker.

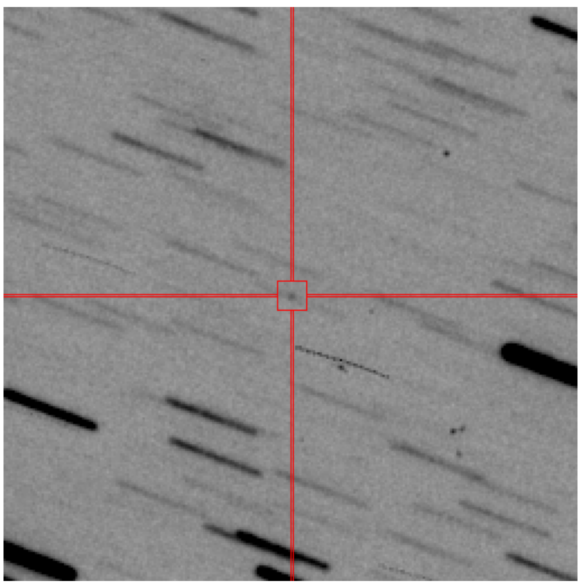

Figure 10. Recovery of 2019 MX1

As shown in Figure 11, three observations were generated of the object, one for each sub-stack. The highest residual is 0.35" which is well within tolerance. The residuals were determined by loading the three observations alongside all other observations of the object known to date, ensuring an accurate orbit determination. As before, the FindOrb software was used for orbit fitting, which is able to compute orbital elements from a series of observations formatted in either MPC1992 or ADES format.

1906 27.58182	Q62	17 23 08.32	-19 11 39.4	.26+	.35-
1906 27.59024	Q62	17 23 08.03	-19 11 28.1	.24+	.29-
1906 27.59862	Q62	17 23 07.72	-19 11 16.9	.09-	.27-

Figure 11. Residuals of June 27 Observations.

11.2 Recovery Example #2: 2019 RC

2019 RC is a Near Earth Asteroid that was found by ATLAS in 2019. At the time of follow-up, only the original four observations were known. These four observations resulted in an ephemeris that indicated a speed of 3.61"/min and a position angle of 80.4 degrees. It also placed the object 15 arcminutes away from its true position. But even manual scanning would have failed, as the indicated motion was dramatically different from that of its true motion of 3.16"/min and position angle of 86.4 degrees. Figures 12, 13, and 14 show the detection of 2019 RC using three different motion vectors.

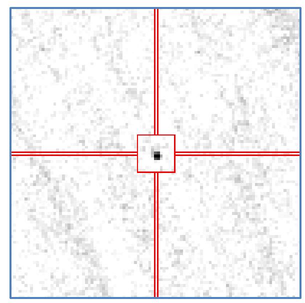

Figure 12. Detection at speed of 3.16"/min

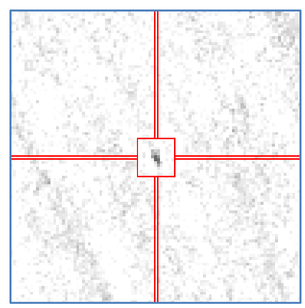

Figure 13. Detection at speed of 3.30"/min

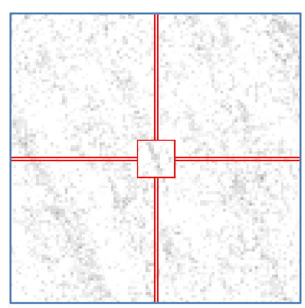

Figure 14. Detection at speed of 3.60"/min

The first detection shown in Figure 11 is that of the object with its true motion, found only by iterating over hundreds of candidate motion vectors. The second detection uses the same position angle but a speed of 3.3"/min. The object is becoming unrecognizable. Finally, the third detection is that of the object using a speed of 3.6”/min. It is no longer recognizable. This is the same speed computed by the ephemeris when using the original four observations of the object. As such, it was not possible to identify the object using the conventional “track and stack” technique. Instead, it was identified using the synthetic tracking method.

11.3 Recovery Example #3: 2018-103B

2018-103B is the booster used for the Chinese lunar probe in the *Chang’e* 4 mission. Images of the object were taken on September 16, 2019. Ephemeris generated from observations of the object one day prior indicated an expected speed of 13.1”/min and position angle of 161.8 degrees.

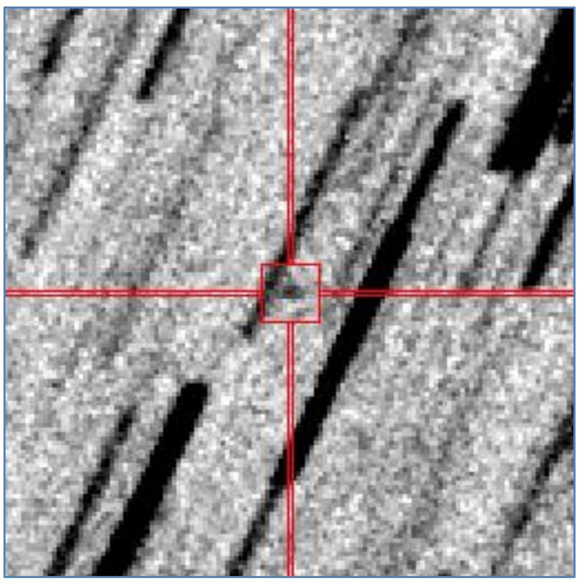

Figure 15. Detection of Chang’e 4 Booster.

Similar to 2019 RC, the ephemeris proved to be not entirely helpful, as the actual speed of the object was determined to be 11.2”/min and its position angle was determined to be 160.0 degrees. And as before, the difference in expected speed versus actual speed rendered the object entirely unrecognizable using the conventional track and stack technique. But with synthetic tracking there was no difficulty in detecting and measuring it.

12. Conclusion

In a short timeframe, several advancements have taken place that dramatically improve the viability of the synthetic tracking technique, both for discovery as well as recovery. As most of the larger (and brighter) asteroids have already been discovered, it becomes clear that one must adopt an approach that enables the detection of increasingly fainter asteroids. Furthermore, due to the economics of telescope aperture, it is optimal to select an approach that can make use of moderate-sized instruments.

As has been shown, synthetic tracking enables the detection of very faint objects even when using such moderate-sized instruments. It also improves upon the utility of the standard “track and stack” technique by automatically evaluating thousands of different motion vectors, enabling the detection of very faint objects even when the motion is not known in advance.

13. Acknowledgements

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14. References

"Summary of PHA and NEA Discoveries." Minor Planet Center. https://minorplanetcenter.net/iau/lists/YearlyBreakdown.html

Parrott, D., "Analysis of NEO Discovery Observations from 2014 to 2019." https://drive.google.com/file/d/1P7492todGQ6-TBhAq565I34ckIUTDx7L/view

"CUDA Benchmarks." Geekbench Browser. https://browser.geekbench.com/cuda-benchmarks

"MPEC 2020-B194." Minor Planet Center. https://www.minorplanetcenter.net/mpec/K20/K20BJ4.html

Shao, M., et al. "Finding Very Small Near-Earth Asteroids Using Synthetic Tracking." (2013). https://arxiv.org/pdf/1309.3248.pdf

Heinze, A., et al. "Digital Tracking Observations Can Discover Asteroids Ten Times Fainter than Conventional Searches." (2015). https://arxiv.org/pdf/1508.01599.pdf

Parrott, D., "One Refractor, One Field: 281 Asteroids, Limiting Magnitude 20.8." https://drive.google.com/file/d/1e0aAEl0NvrgxFW9Q8LgOpfiHdrzTtszb/view

Shao, M., et al. "Synthetic Tracking on a Small Telescope." (2018). https://amostech.com/

TechnicalPapers/2018/Optical-Systems_Instrumentation/Shao.pdf

Beatty, K., "Two Wide Eyes on the Sky." (2010). Sky and Telescope. https://skyandtelescope.org/astronomy-news/two-wide-eyes-on-the-sky/

Do, A., et al. “Interstellar Interlopers: Number Density and Origin of ‘Oumuamua-Like Objects.” (2018). https://arxiv.org/pdf/1801.02821.pdf

Walthert, M., “Meet the Amateur Comet Hunter Who Out-Gazes the Big Telescopes.” (2015). Vice. https://www.vice.com/en_us/article/ypwxbj/meet-the-amateur-comet-hunter-who-out-gazes-the-big-telescopes

Yanagisawa, T., et al. “Small NEO Search Technologies Using Small Telescopes and FPGA.” (2019). https://conference.sdo.esoc.esa.int/proceedings/neosst1/paper/146/NEOSST1-paper146.pdf