Synthetic Tracking on a Small Telescope

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ABSTRACT

Synthetic tracking uses high speed (up to 10 Hz) low noise ($<2e^-$) large format sensors ~16 Mpix along with a multi-vector shift/add algorithm that coadds multiple image frames to increase the signal to noise ratio (SNR) needed to detect (if present) multiple moving objects in the field of view (FOV). We published the application of synthetic tracking to look for asteroids in 2014 (Shao 2014), but recently have applied it more as well to Earth orbiting objects. We have begun testing the data processing graphical processing unit (GPU) array with a small telescope, a 28 cm Celestron RASA telescope and a low cost low noise 16 Mpix CMOS camera at a dark site in California. This system is now operational with a 2 sqdeg FOV and a limiting magnitude between ~16-17.5 stellar magnitudes (mag) depending on a number of observational parameters for short integration times. The instrument can be used to search for NEOs, where we use much longer integration times to get sensitivity ~ 20.5 mag (at new moon). Synthetic tracking provides significant improvements in both sensitivity and astrometric accuracy.

1. INTRODUCTION

Detecting moving objects in space is different than detecting stationary objects. Our telescopes will typically take several short exposure images of the sky and in subsequent analysis look for object that move between the exposures. The key point is that the object has to be detectable in each of the several single exposure images. Furthermore, moving objects can produce a streaked image if the exposure time is too long. An orbiting object moving at the speed of 15 arcsec/sec for a telescope/sensor with 1 arcsec resolution should expose for just 1/15 sec. Longer exposures do not increase the signal, they just increase the contribution from the background/sky noise. Synthetic tracking (ST) avoids this loss of the SNR by combining multiple short exposures and then adding the image stack using a digital shift/add algorithm [1]. Telescopes with large focal planes typically have a mosaic of CCDs detectors.

Large pixel count CCD detectors cannot be read out in 1/15 sec at low noise. However, CMOS detectors are now available with a large pixel count and low read noise ($< 2e^-$) at frame rates of 10's of Hz. One low cost 16 Mpix sCMOS sensor can read out 160 Mpix/sec at $1.6e^-$ read noise. A sensor with this low read noise on a 1m telescope would be sky background limited even for a 22mag/arcsec^2 sky. Modern CMOS sensors allow high frame rates with essentially no read noise penalty. The major difference between synthetic tracking and normal CCD based on our telescopes is that ST can detect moving objects that are theoretically undetectable in a single frame.

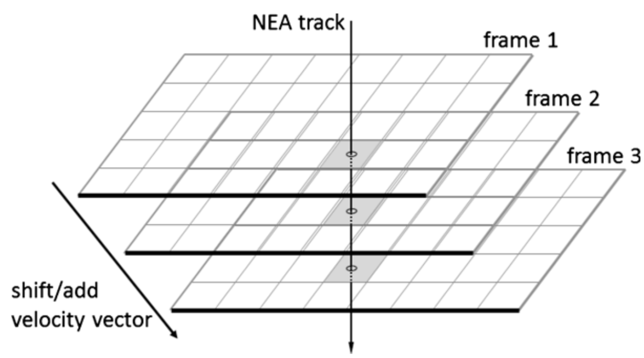

Fig. 1. Shift-and-add concept illustrated: because of the motion of the object, photons are deposited on different pixels of a CCD, but in the synthetic image (with shifted/added frames) the object smear is removed.

Synthetic tracking increase the SNR by adding multiple images while using a digital shift/add algorithm. One apparent drawback to shift and add is that before we detect the object, we do not know in advance what its velocity is and how far and in which direction we should shift subsequent images. Synthetic tracking does a brute force search, performing the shift/add for 1000's of possible velocity vectors. This is now possible with relatively low cost GPU boards that have peak processing speed of~5 Tflop.

By adding N frames, we increase the noise by sqrt(N). The gain in sensitivity comes from several places, one is the ability to take faster exposures, ~1/10 sec, most of the gain comes from coadding ~40 or more images. Last of all, 16 Mpix camera will have smaller pixel sizes, ~1 arcsec; also, for an observatory at a location with 1 arcsec or better seeing as well as 1 arcsec resolution optics, there is the possibility of additional increase in sensitivity [1].

2. TELESCOPE

In order to provide data to test the data processing hardware/software, we installed a small telescope/sensor at a dark site in central California. The telescope is a Celestron RASA 28 cm diameter Schmidt telescope with a f/2.22 prime focus 16 Mpix CMOS camera. The sensor comes from the mass market DSLR market and can take video at 10 Hz with ~1.6e$^-$ read noise. Its major drawback is a relatively low QE. In fact, on the RASA telescope, the peak system QE (~600 nm) is ~30%.

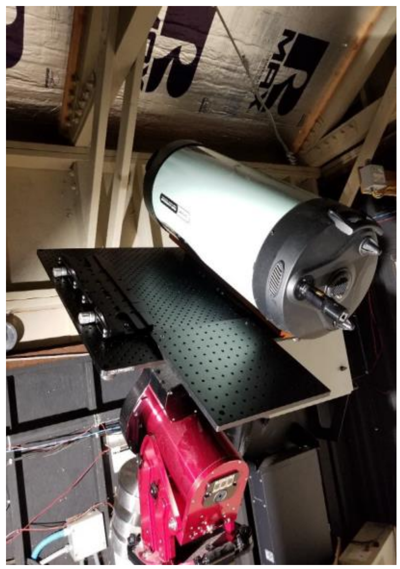

Fig. 2. Celestron 28cm Telescope with 16Mpix CMOS sensor at prime focus (no visible from this angle) used to collect data in this paper.

The 620 mm focal length of the telescope combined with (16 million) 3.8 μm pixels provides a 2 sqdeg FOV and a plate scale of 1.27 arcsec/pixel. The same hardware can be used to search for moving objects in space from MEO orbits to asteroids 0.4 astronomical units (AU) from the Earth.

3. REAL TIME ON-SITE DATA PROCESSING

The data rate for a 16 Mpix sensor at 10 Hz is moderately high, 320 Mbytes/s. Most of the time, it is inconvenient to transmit this data to a supercomputer located in a large city. From the beginning of this effort, we planned to do the synthetic tracking data processing on site in real time. The data processing pipeline has a large number of steps shown in the Figure 3. But by far, the most computationally demanding part is the multi-vector shift/add operation. The current software suite assigns a single GPU to work on a single data cube. In general at 10 Hz video rates, a single GPU cannot complete the shift/add operation in real time. We currently plan to use 4 GPUs so that when the 5-th data cube is ready the 1-st data cube will have finished the data processing. Currently the raw data is also recorded on an M2 SSD drive.

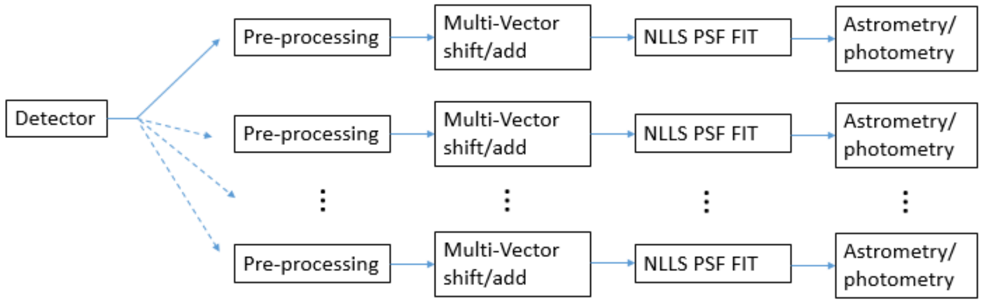

Fig. 3. The data processing pipeline.

A simplified description of the processing steps is described here. The pre-processing part consists of operations such as bias as well as dark and sky subtraction, flat field correction, cosmic ray removal, and frame re-registration to compensate for imperfect telescope tracking. The multi-vector shift/add is the computationally demanding part. After potential moving objects are identified, with an approximate location, and velocity, we perform a linearly moving PSF fit to the data cube with subpixel interpolation of the PSF for each frame for every potential moving object. In this fit we vary the X,Y position of the target, the brightness, and the velocity, V_x, V_y. We also estimate the sky noise in each data cube and set a threshold of 7σ for detection after the PSF fit. The last step, astrometry and photometry consists of picking ~50-100 stars in the FOV and matching them to stars in the GAIA catalog. We use the GAIA positions to solve for an optical distortion model. While the NLLS PSF fit does provide an average brightness for the moving object, the photometry module goes back to the raw data and performs area photometry that is independent of as assumed PSF for each frame of the data cube.

We have performed several experiments to do synthetic tracking data processing in real time and have met the speed requirements for NEO processing in real time. The plan is to do real time processing at the California site for both satellites and asteroids in the near future by the beginning of October 2018.

4. ON SKY TESTS WITH 28-CM TELESCOPE

There are several goals for testing ST with 28 cm telescopes. Algorithms that are great in theory can fail in many dozens of ways when confronted with real data that violate the underlying assumptions in the algorithm. ST is inherently immune to many problems that exist in the CCD-based sensors, but has can have its own set of issues. An ST data cube might consist of ~40-200 images at 10 Hz looking for earth orbiting objects, or a ~80-120 image data cube consisting of 5 sec exposures looking for asteroids. Because we are looking for objects that move linearly in time over the length of the data cube, many sources of false positives in two and three image tracklets are avoided in ST.

The test program with the small 28 cm telescopes have three initial tests/goals, they are 1) verify that ST can achieve high sensitivity by co-adding many images. This would be done by looking for asteroids down to ~20 to 20.5 mag coadding up to ~80-100 images. 2) demonstrate ST can detect multiple moving objects in the same data cube moving at several different velocities with no prior knowledge of the velocity vectors. The third is that ST can make astrometric measurements at the ~50-100 mas level for slow objects like asteroids and < 100 milliarcseconds (mas) level for the Earth orbiting objects in ~4 sec. Since asteroids move much slower than the Earth orbiting objects, this is a test of the advantage of "unstreaking" an image in providing better astrometry. For the Earth orbiting objects what is added is the accuracy of the camera timing.

Figure 4 shows the detection of a previously unknown NEO, with apparent magnitude of 19.0. It was detected with a SNR~24 in a 80 image data set of 5 sec exposures. When we split the data set into four of 20 image sets, the SNR is ~12. We use a detection threshold of SNR=7, which would correspond to a limiting magnitude of 20.2 mag.

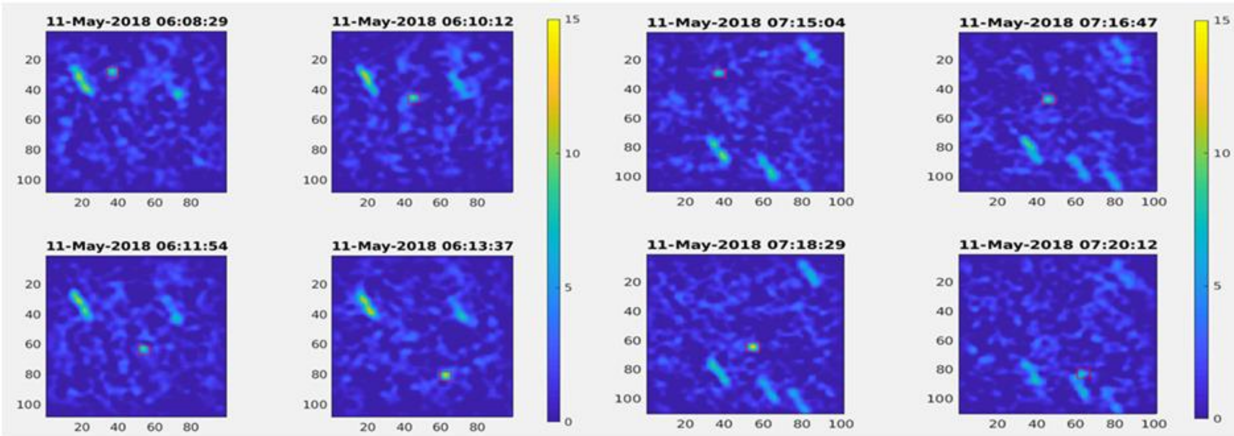

Fig. 4. A previously undetected NEO was detected on 5/11/2018. The object was detected in 2 400 sec data cubes separate by ~4000 sec. The 400 sec date cube, 80 images with 5 sec exposure each image was broking into 4 segments and the synthetic image for each 100 segment is shown above. The velocity of the NEO was 5.9 deg/day.

The NEO was detected on May 5 at RA 14:55:21.626, Dec -5:57.4. The velocity was 0.11 arcsec/sec in RA and -0.22 arcsec/sec in Dec, a velocity of 0.25 arcsec/sec or 5.92 °/day.

Figure 5 is an example of a set of images taken at 10 Hz with the telescope pointed at the GEO belt. The data set can be shift/added in multiple ways. There are a total of 6 earth orbiting objects in the data cube, 5 of them moving in a geosynchronous equatorial orbit and one in an inclined orbits that does not have 24 hr orbit. In this example only one of the objects was so dim, that it would not be detected in a single 0.1 sec frame (with a 28 cm telescope).

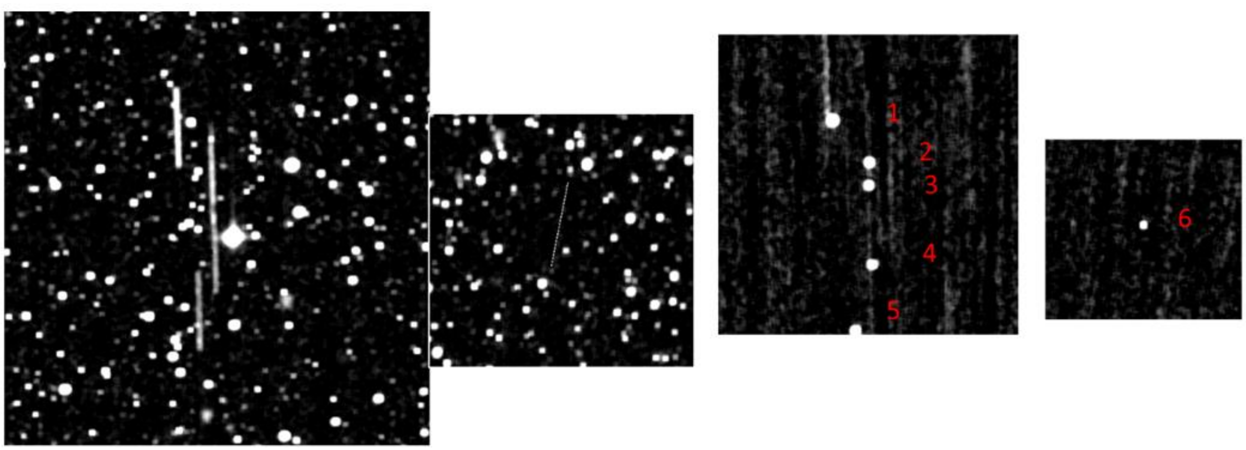

Fig. 5. Left two images were generated coadding images where stars are stationary. The satellites when bright show up as streaks. The small image with the dotted line shows where that satellite would be if it were bright enough to be detected in this zero velocity image. The images on the right were generated by coadding frames at the velocity of the object. Object 6 was in an inclined orbit with a flux of 11 photons/sec and would not have been detected without synthetic tracking.

We used the following data set to demonstrate astrometric precision of the telescope on earth orbiting objects. Figure 4.1 shows three GEO satellites in a 24 second exposure. The RA, Dec was measured over the 24 sec period.

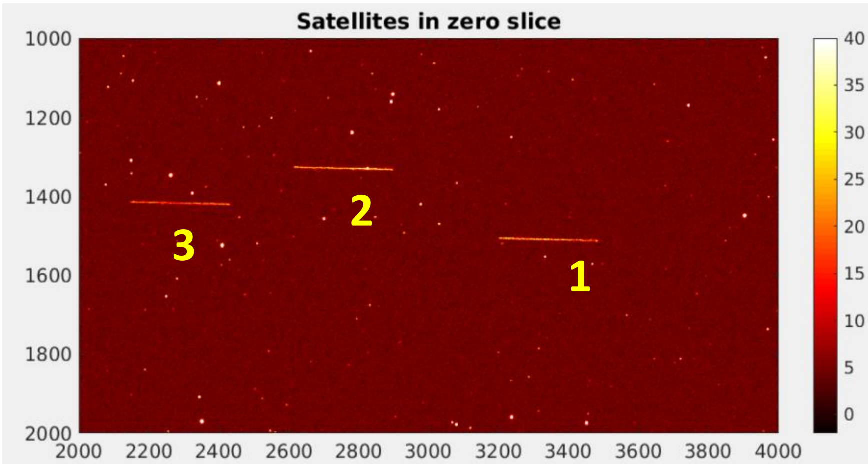

Fig. 6. A zero velocity image of 3 orbiting objects. All objects are bright enough to be seen without synthetic tracking. Normally astrometry of a streaked image would have significant errors in the streak direction.

Figure 7 shows the RA, and Dec of satellite 2. The 24 sec data set was broken into 6 4 sec data cubes and the position of the object was measured. Each 4 sec data cube consisted of 32 images taken at 8 Hz. If the object were detectable in every image, we could fit a Gaussian profile to each image and calculate its centroid. The X,Y positions at each frame could then be fitted to a X,Y position at time 0 and a V_x,V_y velocity. However, since the object may not be detectable in a single image, we fit a moving Gaussian to the whole data cube.

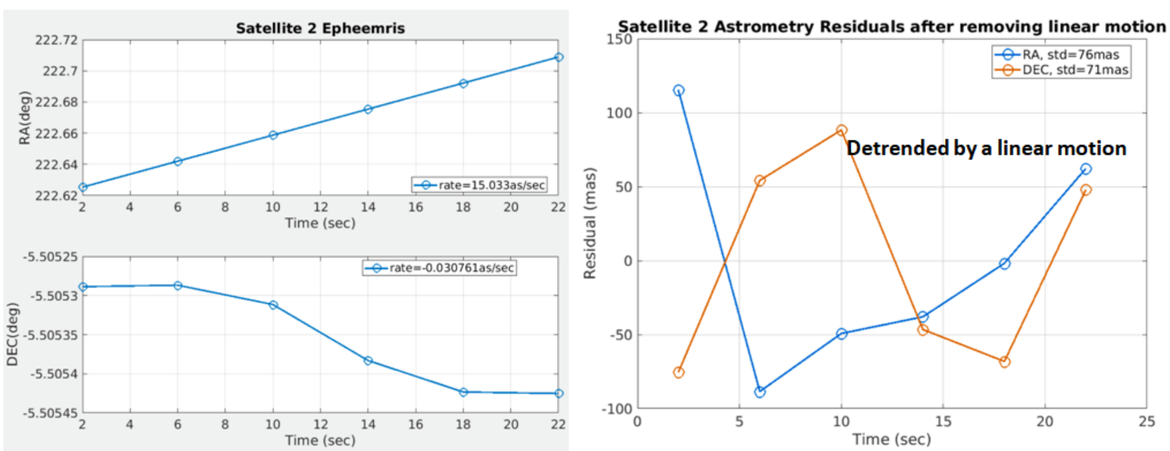

Fig. 7. Astrometry of object 2 with synthetic tracking. The 24 sec data set was split into 6 4 sec data sets and each dot represents 4 sec of data. The left two graphs show RA, Dec of the object versus time. The graph on the right is the residual after straight line motion is subtracted from the RA, Dec versus time on the left.

After removing a straight line motion, the residual are show in the right side of Figure 7. The rms residuals in both RA and Dec are a bit less than 0.08 arcsec. Astrometry of dozens of satellites show residuals between 70-100 mas for a 4 second measurement. We believe that the accuracy should improve as sqrt(N) as more images are averaged. Synthetic tracking astrometry of NEOs [2] has demonstrated ~10-20 mas accuracy for long (2 min) integrations.

These small telescopes can also be used to search for NEOs. For a data set consisting of 100 of 5 second exposures, with a 21 mag/arcsec^2 sky background and ~30% total system QE, we expect the SNR=7 limiting magnitude to be ~20.6 mag. Our observational data is not quite that good, falling short by ~0.2-0.3 mag. We are looking into why that is the case. However, still a NEO search at 20.7 mag is still quite good given that we are not sensitive to streak related loss of sensitivity. Because of this moderately high sensitivity is possible only with very long integration times, (500 sec), our sky coverage (sqdeg/hr) is much less than current larger telescopes like Panstarrs. However it is possible to compensate for that by using multiple 28 cm telescopes. Our simulations of NEO detections show that an array of ~6 of 28 cm telescopes would be roughly equal in performance to all current NEO search telescopes combined. The advantage of this array of small telescopes is their very low cost, which is less than ~$10K each.

5. FUTURE TESTS

Since ST measures both position and velocity, we have a prediction of where the object is in the near future just with a linear extrapolation. The addition of velocity information, should simplify linking observation at epoch with a subsequent observation. One complication of follow up observations with single exposure CCD images is that objects exactly at the threshold of detection have a 50% probability of not being detected in a follow up observation. For ST, we can increase the integration time on the follow up observations from 7σ to say 10σ. With Gaussian noise, that would provide a >99% probability that the follow up observation would detect the object. In a similar fashion, for false negative testing, we can to use a "known" faint moving object, reduce the size of the data cube lowering its SNR and see when it's no longer detected. The ability to vary the integration time and theoretical sensitivity make it easier to derive accurate statistics on false positives and false negatives. This ultimately lets the final user select the sensitivity and false positive rates that are acceptable.

Future tests will be interspersed with a regular automated campaign to search for NEOs. However, the future tests will concentrate on collecting statistics for false positives, false negatives as well as designing an observing program to automate "follow up" observations. Currently NEO observations of fast moving objects, especially smaller NEO with fast angular motion, are easily lost after initial discovery. We will be looking to see if the use of both position and velocity information can reduce the % of objects subsequently lost.

6. SUMMARY

Synthetic tracking is a computational technique to detect moving objects by using a shift/add algorithm in a massively parallel computer. ST does not have a "hard" limiting magnitude for fast moving objects, SNR increases as sqrt(time). However, on average, ST offers roughly order of magnitude greater sensitivity, order of magnitude better astrometric accuracy when used on the same optical system as prior generation CCD based instruments. The advantage of synthetic tracking increase as the velocity of the object increases. But its use on large telescopes with mosaic focal plane is not possible at present because the high speed, low noise CMOS detectors are not currently edge to edge but a table. However there are significant economic advantages to using small to moderate sized telescopes with synthetic tracking because the cost of a telescope grows faster than its collecting area. There is a significant cost break when one can use mass produced small telescopes and mass produced CMOS sensors.

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7. REFERENCES

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